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Life-Cycle Assessment: Substantiating Sustainable Design for Commercial Buildings

Robert Burak, P. Eng.
President, Canadian Precast/Prestressed Concrete Institute (CPCI)

Lindita Bushi, PhD. Eng.
Senior Research Associate, Athena Sustainable Materials Institute (ASMI)

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Goals of the study according to ISO 14040/44:2006 (1)

- **The reasons for carrying out the study**

  … To better understand precast concrete's environmental life cycle performance in Canadian mid-rise precast concrete buildings relative to alternative structural and envelope systems in accordance with the ISO 14040:2006 and 14044:2006.

- **The intended application**

  … To disseminate information on the LCA of precast concrete that is based on the most complete and up-to-date life cycle inventory data for Canadian cement and concrete products.

Goals of the study according to ISO 14040/44:2006 (2)

- **The intended audience**

… The intended audience is architectural, engineering, and specifying professionals, academia, governmental organizations, and other interested parties who require reliable information on sustainable building design practices.

- **Comparative assertions**

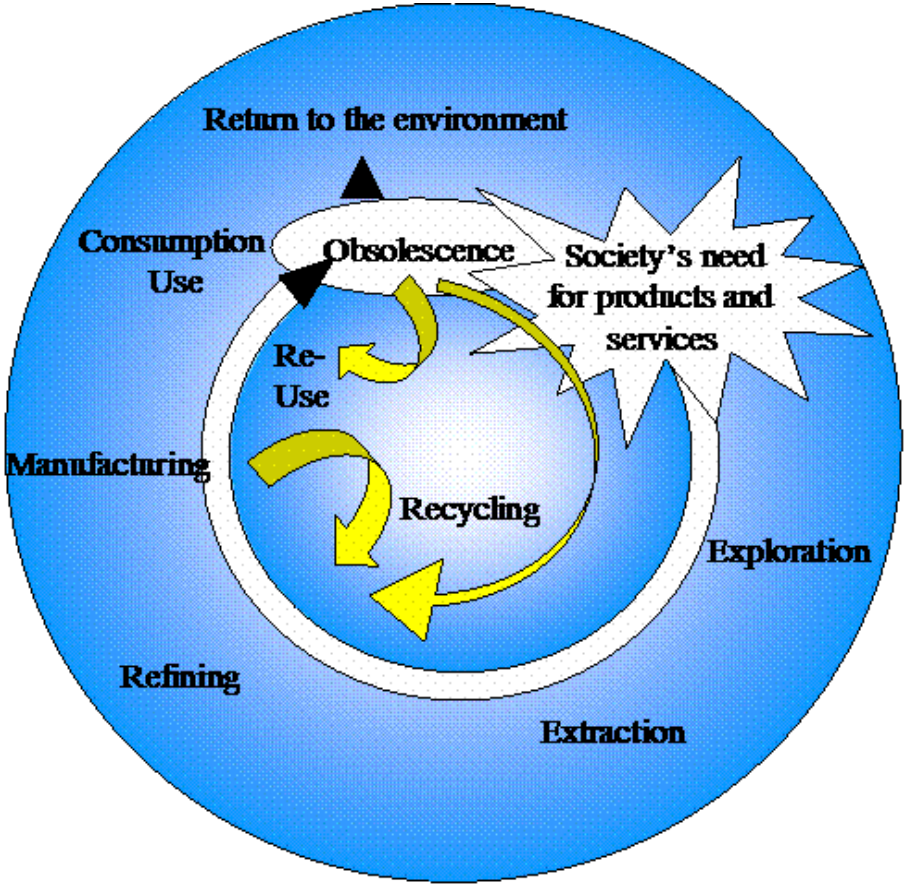
… This LCA study includes a comparative assertion intended to be disclosed to the public and a critical review was conducted by an independent external panel of LCA and technical experts as per Clause 7.3.3, ISO 14044:2006.

Introduction to LCA

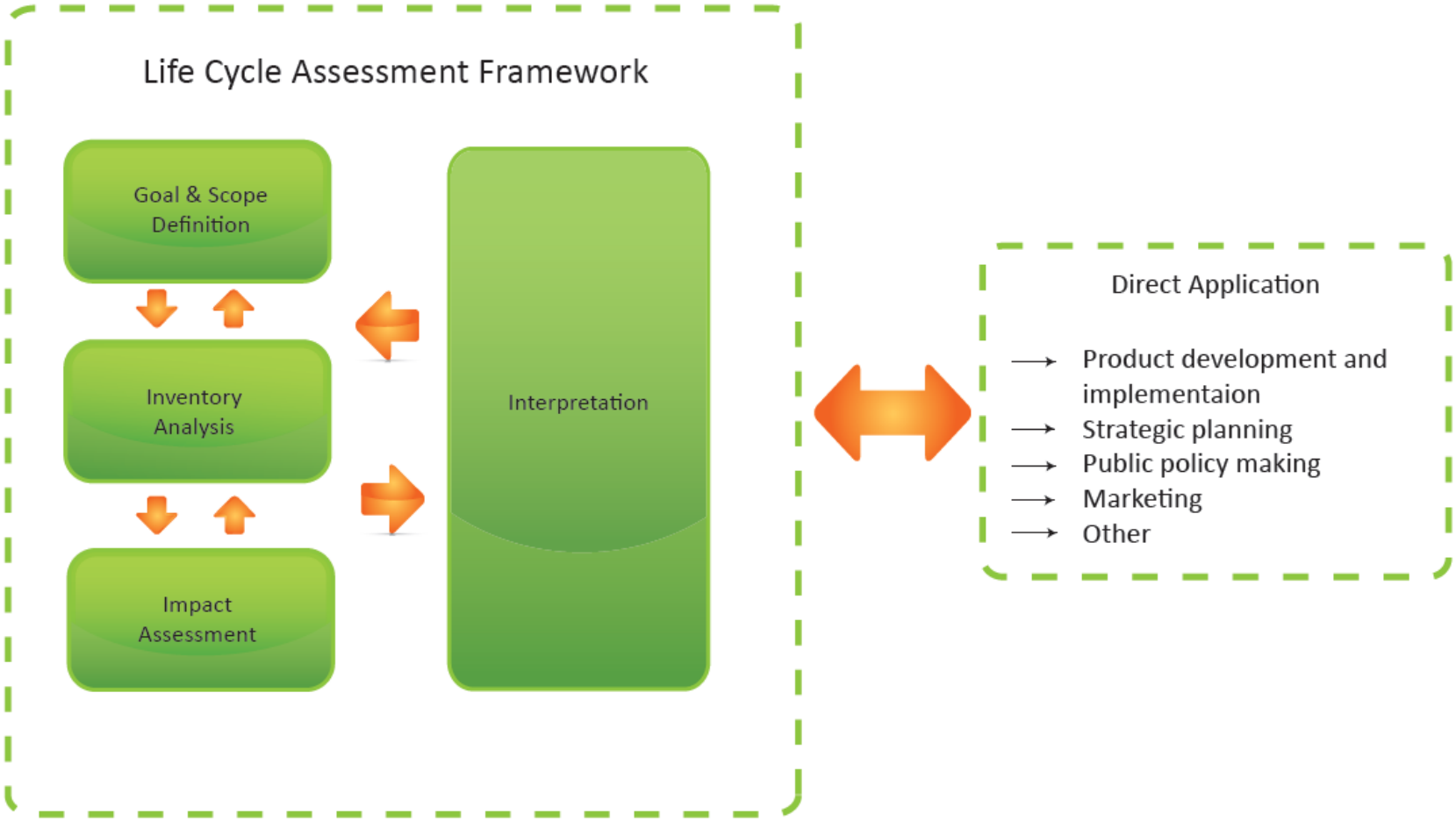
Life Cycle Assessments...

... address the environmental aspects and potential environmental impacts (e.g. resource use and environmental consequences of releases) throughout a product's life cycle from raw material acquisition through production, use, end-of-life treatment and disposal (i.e. cradle-to-grave).

[ISO 14040:2006]



LCA Phases



[ISO 14040:2006]

Scope of the Study

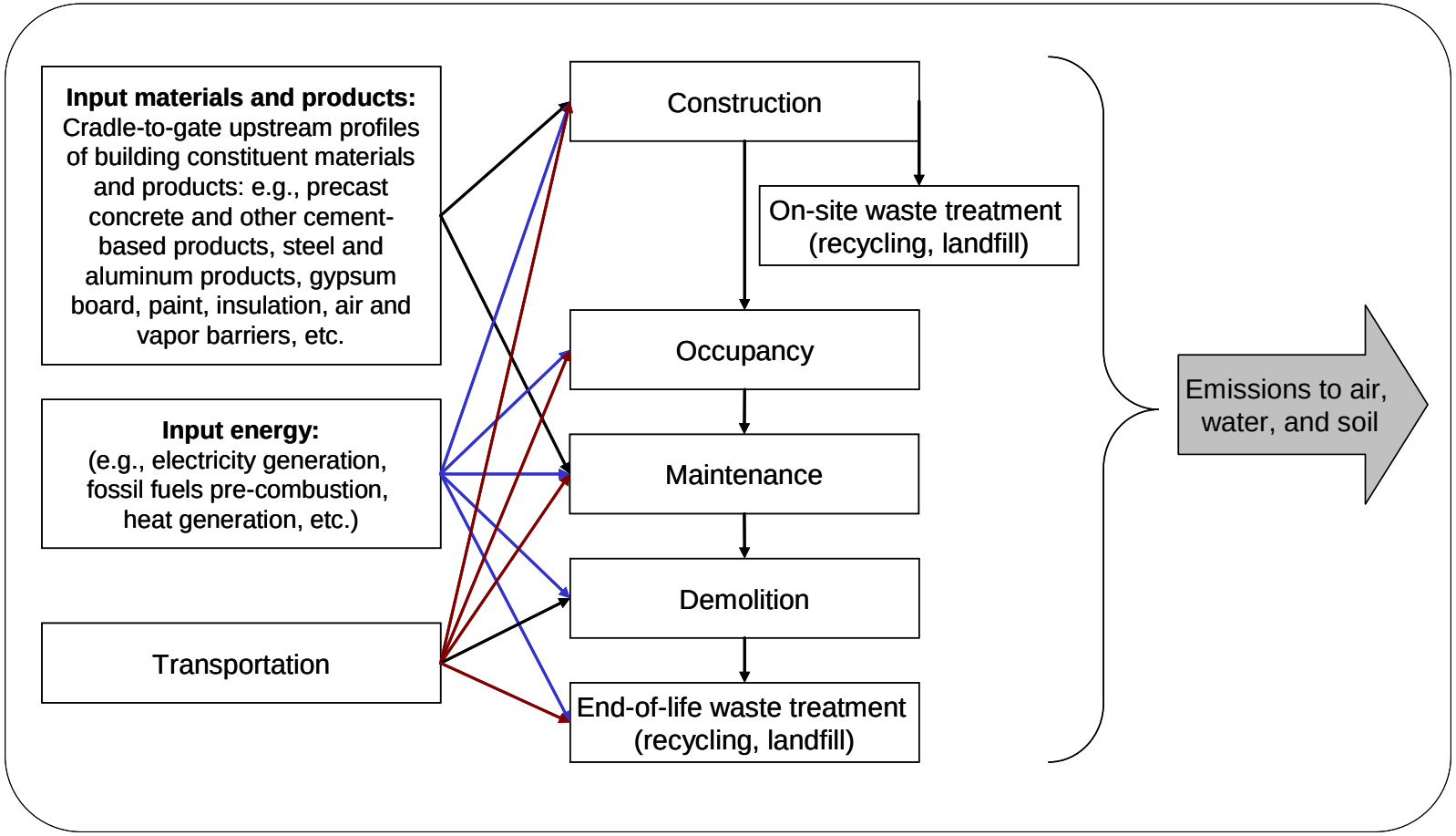
- Product(s) to be studied
- Product System Boundaries
- Functional unit
- Cut-off criteria
- Allocation procedures
- LCIA Methodology
- Data Quality Requirements
- Type of Critical Review
- Data sources and primary data collection
- Building and Location Description

Product(s) to be studied

Typical commercial building with plan dimensions 27.4 by 36.6 m (90 by 120 ft) and gross floor area 5017 m^2 (54,000 ft^2), with 5 (five) variations of **building envelope** and 3 (three) variations of **structural framing** in two Canadian locations (Toronto, Vancouver).

Envelope and abbreviation	**Structure and abbreviation**		
	Steel (S)	**Cast in place concrete (C)**	**Precast concrete (P)**
Curtain wall (CW)	CW-S	CW-C	CW-P
Brick and steel stud (S)	S-S	S-C	S-P
Precast concrete (P)	P-S	P-C	**P-P**
Insulated precast concrete (Pi)	Pi-S	Pi-C	Pi-P
Insulated precast concrete and thin-brick veneer (Pib)*	Pib-S	Pib-C	Pib-P

Building System Boundaries



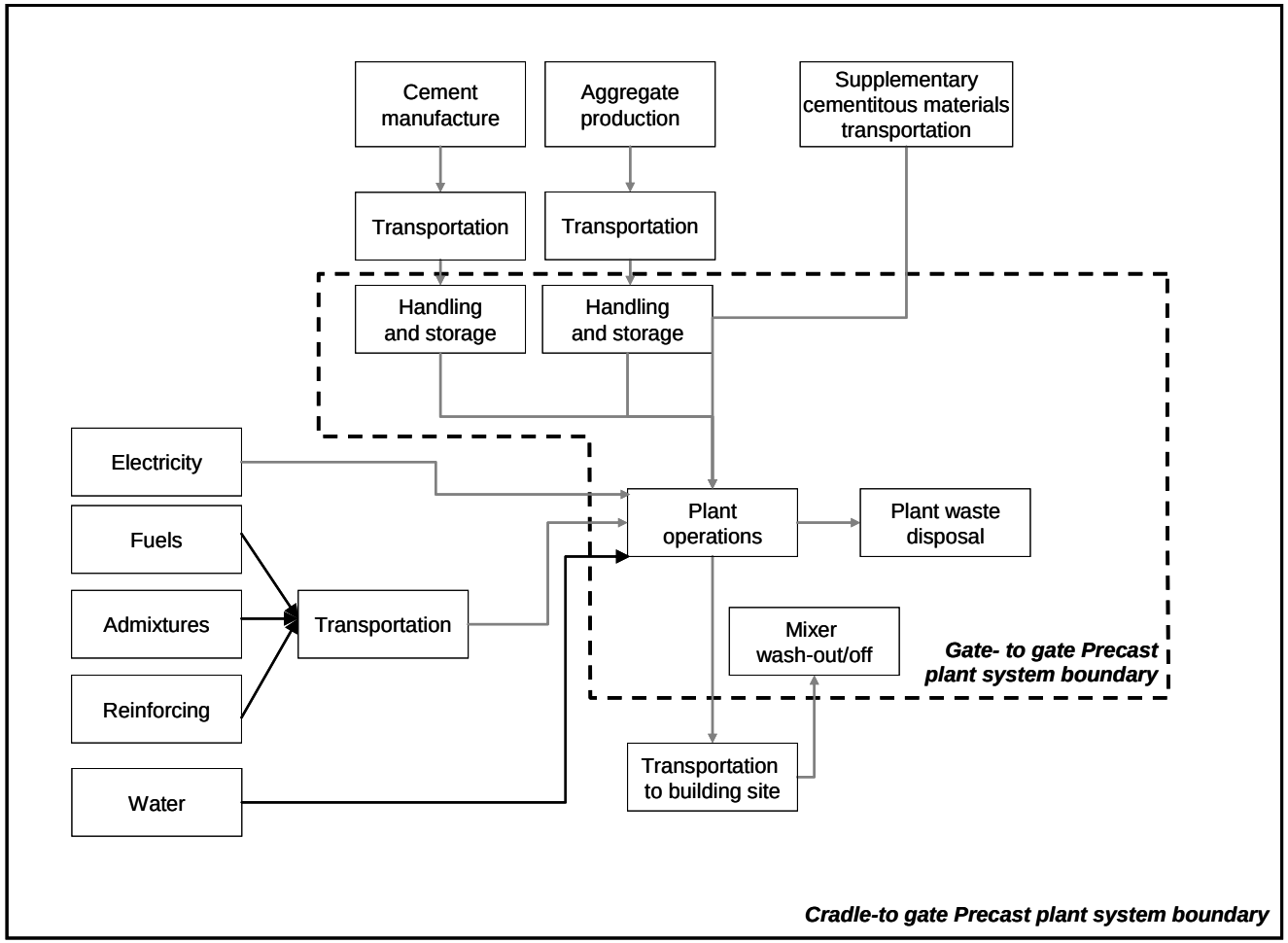
Building system boundary

Functional Unit

… the functional unit is a ***five-story commercial office building*** which meets minimum building energy code requirements R_{SI}-value (R-value) and provides conditioned office space for approximately 130 people.

The functional unit includes both the ***physical*** building and the ***service*** the building provides, which is conditioned space for occupants. Conditioned space consists of maintaining thermostat set points of 21°C (70°F) for heating, 24°C (75°F) for cooling, 2°C (4°F) throttling range, and night setback temperatures of 13°C (55°F) for heating and 37°C (99°F) for cooling. The service life of the building is assumed to be 60-years.

Precast Plant System Boundaries



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Cut-off Criteria

- **Mass**

… all input flows that cumulatively contribute less than 1% of the total mass input of the product system being modeled can be excluded, providing its environmental relevance is minor.

- **Energy** –

… all input flows that cumulatively contribute less than 1% of the total product system's energy inputs can be excluded, providing its environmental relevance is minor.

- **Environmental relevance** –

… if an input flow meets the above two criteria, but is determined (via secondary data analysis) to contribute 2 % or more to any product life cycle impact category (see below), it is included within the system boundary.

Allocation procedures

Allocation

… is defined as partitioning the input or output flows of a process or a product system between the product system under study and one or more other product systems.

ISO three stepwise approach

Step 1. Dividing the unit process or expanding the product system

Step 2. Physical allocation

Step 3. Economic allocation

LCIA Methodology (1)

Impact category	Indicator result	Characterization method	Level of site specificity selected
Global warming	kg CO2 –eq.	TRACI	Global
Acidification	kg H+	TRACI	North America
Ozone depletion	kg CFC-11	TRACI	Global
Eutrophication	kg N water	TRACI	North America
Particulate matter	kg PM2.5	TRACI	North America
Photochemical smog	kg ethylene	TRACI	North America
Solid waste	kg	Sum of LCI flows	North America
Water use	kg	Sum of LCI flows	North America
Abiotic resource depletion, excluding energy	kg antimony/yr	CML 2001	Global
Total primary energy*	MJ	CED adapted	Global

LCIA Methodology (2)

Impact category	Indicator result	Characterization method	Level of site specificity selected
Total primary energy*	MJ	CED adapted	Global
Non-renewable, fossil†	MJ		
Non-renewable, nuclear†	MJ		
Renewable (solar, wind, hydro, geothermal)†	MJ		
Renewable (biomass)†	MJ		
Feedstock, fossil†	MJ		
Feedstock, biomass†	MJ		

Data Quality Requirements

- From all the available life cycle inventory data and metadata that could be used, preference has been given to the most recent product-specific data for Canada and North America representing an average level of technology.

- When North American LCI data were not available, European data sources (such as, Ecoinvent v 2.2) have been used, but adjusted to take into consideration North American upstream resource, electricity, materials and downstream product transportation.

Type of Critical Review

Since this LCA study includes a comparative assertion intended to be disclosed to the public, an **independent external panel of LCA and technical experts** has critically reviewed the **methodology and results** as per Clause 6.3, ISO 14044:2006.

Critical Review Process

The **critical review process** shall ensure that

- the **methods** used to carry out the LCA are consistent with ISO 14044:2006 International Standard,
- the **methods** used to carry out the LCA are scientifically and technically valid,
- the **data** used are appropriate and reasonable in relation to the goal of the study,
- the **interpretations** reflect the limitations identified and the goal of the study, and
- the **study report** is transparent and consistent.

Data sources (1)

LCI input data	Time frame	Geographical representativeness	Technological representativeness	Source	Primary or secondary data
Common primary fossil fuels (including pre-combustion	2004-2008	North America	Average	U.S. LCI Database	Secondary
Electricity generation and delivery	2007	Canada	Average	U.S. LCI Database, IEA & DOE	Secondary
Cement	2006-2008	Canada	Average	PCA	Primary
Ready-mixed concrete	2006-2008	Canada	Average	PCA survey	Primary
Precast concrete	2008	Canada	Average	CPCI surveys	Primary
Steel products	2000; 2007	Worldwide; adjusted to North America	Average	World Steel Association; Canadian Steel Industry Association	Secondary
Aluminum products	2004/2005	Worldwide; adjusted to North America	Average	International Aluminum Institute	Secondary

Data sources (2)

LCI input data	Time frame	Geographical representativeness	Technological representativeness	Source	Primary or secondary data
Float glass	2005	Adjusted Canada	Average	Ecoinvent	Secondary
Clay brick	2008	Canada	Average	Athena Database	Secondary
Insulation, EPS, XPS, polyisocyanurate	2007	Canada	Average	American Chemistry Council (ACC)	Secondary
Insulation, fiberglass and rockwool	2006	Adjusted to Canada	Average	Ecoinvent	Secondary
Modified bitumen roofing	2004	Canada	Average	Athena Institute	Secondary
Vapour retarder	2007	Canada	Average	ACC	Secondary
Raw material and final product transport	2004/2009	Canada	Average	Surveys, Statistics Canada	Primary, Secondary
End-of Life	2000/2007	Canada	Average	Athena Database ICF 2005*	Secondary

Primary data collection from precast concrete plants

- **Reference year- 2008 (12 months)**
- **3 Precast Concrete Plants:** Richmond, British Columbia; Winnipeg, Manitoba; Terrebonne, Quebec**.**
- **Generic Data collection system (DCS)**
  - Identification of the data that needs to be collected;
  - Planning when, where, and how data are to be collected and by whom;
  - Identification and treatment of data gaps as per ISO requirements;
  - Data collection process;
  - Documentation of the resulting data, together with possible sources of error, bias or lack of knowledge;
  - Averaging the data across the plants;
  - Validation of the data by CPCI and verifiers; and
  - Communication of the data and its documentation.

Concrete Mix Designs and Properties

Mix constituents and property, unit per m3 (unless noted otherwise)	Hollow-core slab	Precast wall panel, beams, and columns	Cast-in-place structural concrete*	Cast-in-place non-structural concrete†
Portland cement, kg	326	354	268	179
Fly ash, kg	53	79	67	44
Fine aggregate, kg	961	943	712	831
Coarse aggregate, kg	920	759	1187	1127
Mix water, kg	126	166	141	141
Water-reducing admixture, kg	0.4	3.0	3.0	1.2
Total, kg	2387	2305	2374	2323
Mix property				
Water–cementitious materials ratio	0.33	0.38	0.42	0.63
Cement substitution with SCM, %	14	18	20	20
Nominal compressive strength, MPa	40 to 50	35 to 40	35	20
Fluid volumetric conversion				
Water used in mix , L	97	127	108	108
Chemical admixtures, L	1	5	n.d.	8

* Beams, columns, footings, and topping slab for hollow-core slab; † Slab on ground; Note: SCM = supplementary cementitious material; n.d. = no data.

Building and Location Description

- Size, Shape and Climate
- Windows and Roofs
- Slab-on-ground, foundation walls, and footings
- Floors and Interior walls
- Structural framing
- Thermal performance of exterior envelope
- Items not included

Size, Shape and Climate

Size and shape

- Five-story commercial buildings with plan dimensions 27.4 by 36.6 m (90 by 120 ft).
- Column grid spacing of 9.1 by 12.2 m (30 by 40 ft).
- The building height of 19.2 m (63 ft) is based on 4.6 m (15 ft) for the first story and 3.7 m (12 ft) for the remaining four stories.

Climate

- **Vancouver, British Columbia** - a cool climate (Climate Zone 5C)—and
- **Toronto, Ontario** - a cold climate (Climate Zone 6A).

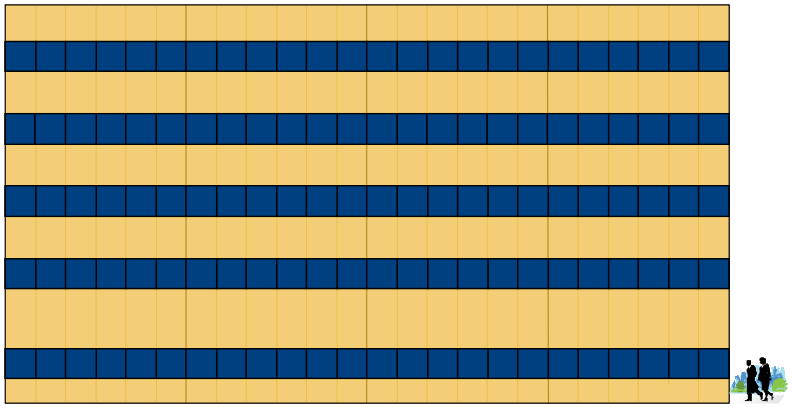
Windows and Roofs

• Band of windows each measuring approximately 1.5 by 1.5 m (5 by 5 ft).

• Windows are non-recessed; equally spaced; and non-operable (no blinds or shading devices).

•The overall window to wall ratio is 0.40.

• The roofs consist of board insulation, cover board, and built-up waterproofing membrane.



Slab-on-grade, foundation walls, and footings

- The ground-level floor consists of 15 cm (6-in.) cast-in-place concrete slab-on-ground, underslab vapour retarder, and rigid insulation in Toronto (required by energy code).

- Foundation walls and footings are reinforced cast-in-place concrete.

- The dimension and material quantities for foundation walls and footings is determined using ENERCALC structural engineering software.

Floors and Interior walls

- Interior floors of the precast concrete frame buildings consist of 20 cm (8 in.) hollow core concrete with a 5-cm (2in.) concrete topping slab.

- Interior floors of the steel frame buildings consist of ribbed steel deck with concrete topping whose thickness varies between 5 and 10 cm (2 and 4 in.).

- The interior walls consist of non-structural steel studs (cold-formed steel) and gypsum wallboard. Interior partitions and partition walls (for example, between office cubicles and interior offices) are excluded because its contribution is the same across all buildings and all climates.

Structural framing

- For the **steel framing**, the RAM Steel structural engineering software (version 13.0) was used.

- For **cast-in-place** *columns and beam-integral floor slabs*, manual engineering calculations were used.

- For **precast concrete** *beams, columns, and hollow-core slabs*, the PCI Handbook was used with manual engineering calculations, but the same resulting sizes can be obtained from the CPCI Design Manual.

Thermal performance of exterior envelope (1)

- The thermal performance of the exterior envelope assemblies is based on the requirements in ASHRAE Standard 90.1-2007 *Energy Standard for Buildings Except Low-Rise Residential Buildings.30*

- The Canadian Model Energy Code was derived from ASHRAE 90.1

- Both the Ontario and British Columbia energy codes reference ASHRAE 90.1.

Thermal performance of exterior envelope (2)

Table Energy Code Envelope Requirements (SI Units)*

Climate zone	City	Fenestration		CW fenestration	Roof R_{SI}-value	CW wall R_{SI}-value	Mass wall R_{SI}-value	Slab R_{SI}-value & depth
		U-factor	SHGC	U-factor				
5C	Vancouver	3.12	0.40	2.56	3.5	2.3 + 1.3	2.0 ci	NR
6A	Toronto	3.12	0.40	2.56	3.5	2.3 + 1.3	2.3 ci	R-1.8 for 600 mm

*Adapted from *ASHRAE 90.1-2007*, Table 5.5. U-factor in W/(m^2·K) and R_{SI}-value in (m^2·K)/W.
Note: CW = curtain wall; NR = no insulation requirement; ci = continuous insulation across structural members without thermal bridges other than fasteners and service openings; and "2.3 + 1.3" = R-2.3 cavity insulation plus R-1.3 continuous insulation.

Thermal performance of exterior envelope (3)

Table Conventional Precast Walls Used to Meet Building Energy Code Requirements

		R_{SI}-value*	
Layer (outside to inside)	**Material**	**Vancouver**	**Toronto**
Exterior air film	Air, 24 km/h wind	0.03	0.03
Precast single wythe	Concrete, 150 mm	0.07	0.07
Rigid insulation, continuous	Extruded polystyrene, thickness, mm	60	70
	Extruded polystyrene, R_{SI}-value	2.03	2.38
Thermal break air space	Air space	minimal	minimal
Framing	65 mm	0.14	0.14
Interior finish	Gypsum wallboard, 16 mm	0.10	0.10
Interior air film	Air, horizontal heat flow	0.12	0.12
Total R_{SI}-value, $m^2 \cdot K/W$		**2.48**	**2.83**
U-factor, $W/m^2 \cdot K$		**0.4**	**0.35**

* R_{SI}-value except where noted; R_{SI}-value in $(m^2 \cdot K)/W$; U-factor in $W/(m^2 \cdot K)$; and R_{SI}-value of layers containing framing includes the effect of thermal bridging which reduced thermal performance.

Thermal performance of exterior envelope (4)

- The modeled rate of infiltration is based on the typical Canadian maximum rate of 0.5 L/s ·m2 of envelope area when measured at a pressure difference of 75 Pa.

- All buildings envelopes, whether curtain wall, brick on steel stud backup, or precast concrete, are all presumed to be designed and constructed to be equally airtight.

Items not included

No.	Items not included	Reason for exclusion
1	Fireproofing	Falls under the cut-off criteria of this LCA study
2	Furniture	Common to all buildings
3	Electrical cooper wire	
4	Data cables	
5	Heating, ventilation, and air-conditioning systems	
6	Fire suppression systems	
7	Control systems	
8	Ceramic tile	
9	Carpet tile	
10	Elevators	
11	Plumbing	
12	Ceiling tiles	
13	Lighting	
14	Doors	
15	Hardware	

Annual Energy Use (1)

- **EnergyPlus** whole-building energy simulation software, developed by the U.S. Department of Energy and other parties;

- It simulates the complex interactions between climate; internal gains from lights, people, and equipment; building form and fabric; HVAC systems; and renewable energy systems;

- Interaction between building operation, envelope, systems that use energy, and the outdoor environment. How the HVAC system responds to these interactions is how the ***modeled buildings differ from each other***.

- Heating, cooling, lighting (including exterior lighting), and interior equipment (including elevators) were simulated for each combination of building envelope and structure at **10-minute intervals** and summed over a typical year.

Annual Energy Use (2)

As-Modeled (Reduced) U-factors and RSI/R-values

City	Building envelope	Wall U-factor	Wall U-factor	Overall wall R_{SI}-value (1/U)	Overall wall R-value (1/U)
		W/m^2·K	But/hr·ft^2·°F	m^2·K/W	hr·ft^2·°F/Btu
Vancouver	Curtain wall (CW)	0.433	0.0763	2.31	13.1
	Brick and steel stud (S)	0.498	0.0877	2.01	11.4
	Precast concrete (P)	0.424	0.0747	2.36	13.4
	Insulated precast concrete (Pi)	0.430	0.0757	2.33	13.2
	Insulated precast concrete and thin-brick veneer (Pib)	0.428	0.0754	2.34	13.3
Toronto	Curtain wall (CW)	0.433	0.0763	2.31	13.1
	Brick and steel stud (S)	0.444	0.0782	2.25	12.8
	Precast concrete (P)	0.372	0.0655	2.69	15.3
	Insulated precast concrete (Pi)	0.376	0.0662	2.66	15.1
	Insulated precast concrete and thin-brick veneer (Pib)	0.374	0.0659	2.67	15.2

Annual Energy Use (3)

Baseline Building Assembly (P-P)	Annual site energy use, GJ	
	Vancouver	Toronto
Heating	427	705
Cooling	115	203
Interior lighting	610	610
Exterior lighting	232	233
Interior equipment	908	908
Elevators	165	165
Fans	71	77
Pumps	0.4	0.4
Water Systems	54	58
Total	**2583**	**2958**

Annual Energy Use (4)

TABLE 1. ANNUAL SITE ENERGY USE BY ENERGY SOURCE, VANCOUVER

	Annual site energy use, GJ														
Building	**CW-S**	**CW-C**	**CW-P**	**S-S**	**S-C**	**S-P**	**P-S**	**P-C**	**P-P**	**Pi-S**	**Pi-C**	**Pi-P**	**Pib-S**	**Pib-C**	**Pib-P**
Electricity	2596	2504	2537	2576	2490	2519	2567	2481	2512	2550	2469	2501	2550	2469	2498
Natural gas	64	71	69	67	74	73	66	73	71	67	75	73	67	75	73

TABLE 2. ANNUAL SITE ENERGY USE BY ENERGY SOURCE, TORONTO

	Annual site energy use, GJ														
Building	**CW-S**	**CW-C**	**CW-P**	**S-S**	**S-C**	**S-P**	**P-S**	**P-C**	**P-P**	**Pi-S**	**Pi-C**	**Pi-P**	**Pib-S**	**Pib-C**	**Pib-P**
Electricity	2854	2767	2802	2838	2752	2787	2816	2729	2764	2804	2727	2756	2803	2726	2755
Natural gas	171	199	189	178	206	197	175	203	194	178	203	197	178	203	197

Maintenance, Repair and Replacement (1)

• The study building is assumed to be an owner occupied office building with a service life of 60 and 73 years;

• The following eight study assemblies were identified as undergoing maintenance:

1. Interior partitions (all cases)
2. Roof waterproofing system (all cases)
3. Windows (all cases except buildings with curtain wall)
4. Curtain wall
5. Brick and steel stud wall
6. Conventional precast panel wall
7. Insulated precast panel wall
8. Insulated precast with brick veneer panel wall

Maintenance, Repair and Replacement (2)

• The study building is assumed to be an owner occupied office building with a service life of 60 and 73 years

$$Q_{m,n}\ tot = Q_{m,n} * (SL - P_n) / P_n * (100\%+WF_m)/100$$

Where,

m	material or energy
n	maintenance stage activity
$Q_{m,n}$	quantity of material or energy m for activity n- e.g. 1 ton material;
SL	building service life (years)- e.g. 73 years
P_n	activity rate for activity n (years)- e.g. 20 years
WF_m	waste factor for material or energy m (%)- e.g. 5%

Example:

$Q_{m,n}$ tot = 1 * (73 – 20) / 20 * (100+5)/100 = 2.78 ton of material for 73 years service life

End of Life

Material to be recycled by establishments designated under Ontario's 3Rs Regulations

Waste Type	Construction over 2000 m^2	Demolition over 2000 m^2
Brick and concrete	X	X
Drywall (unpainted)	X	X
Steel	X	X
Wood untreated	X	X

Construction and Demolition Waste End-of-Life Scenarios

Material	Reused	Recycled	Landfilled
Brick and concrete[1]	…	100%	…
Drywall[2]	…	15%	85%
Steel[3]	…	RR = 98% (S) & 70% (R)	…
Aluminum[4]	…	RR = 95%	…
Glass & other materials[5]	…	…	100%

1. Assume all brick and concrete crushed on-site with 50% remaining on site as fill and the remainder trucked off-site 60 km to be used as a substitute for aggregate.

2. Assume gypsum on-site construction off-cuts are recycled (100%), with the remainder sent to landfill.

3. SRI 2011 data and WSA 2008 LCI EOL modeling are applied for structural and reinforcing steel products (Section 6.5).

4. IAI 2007 and EAA 2008 data and LCI EOL modeling are applied for aluminum products (Section 6.5).

5. Assume all float glass is landfilled (window or curtain wall)

Life Cycle Inventory (LCI) Model (1)

Black-box

Commercial building

Top-down approach

Step 1- Define building structure and envelope (assemblies)

Step 2- Define building sub-assemblies (both basic & specific) per each assembly

Step 3- Define building constituent element (material, product, or process) per each sub-assembly

Life Cycle Inventory (LCI) Model (2)

Step 1	**Assembly: e.g. Baseline (P-P)** Building Envelope: Precast concrete (P) Building Structure: Precast concrete (P)
Step 2	**Specific sub-assemblies** 1. Footings and exterior wall foundation (for concrete structures) 2. Precast concrete (conventional panel) 3. Windows (not curtain wall) 4. Precast concrete beams and columns 5. Hollow-core floors 6. Elevator and stairwell walls (all concrete buildings)
	Basic sub-assemblies 1. Interior partition walls; 2. Slab on ground; 3. Steel stairs with concrete topping; 4. Roof waterproofing system; and 5. On-site construction processes.

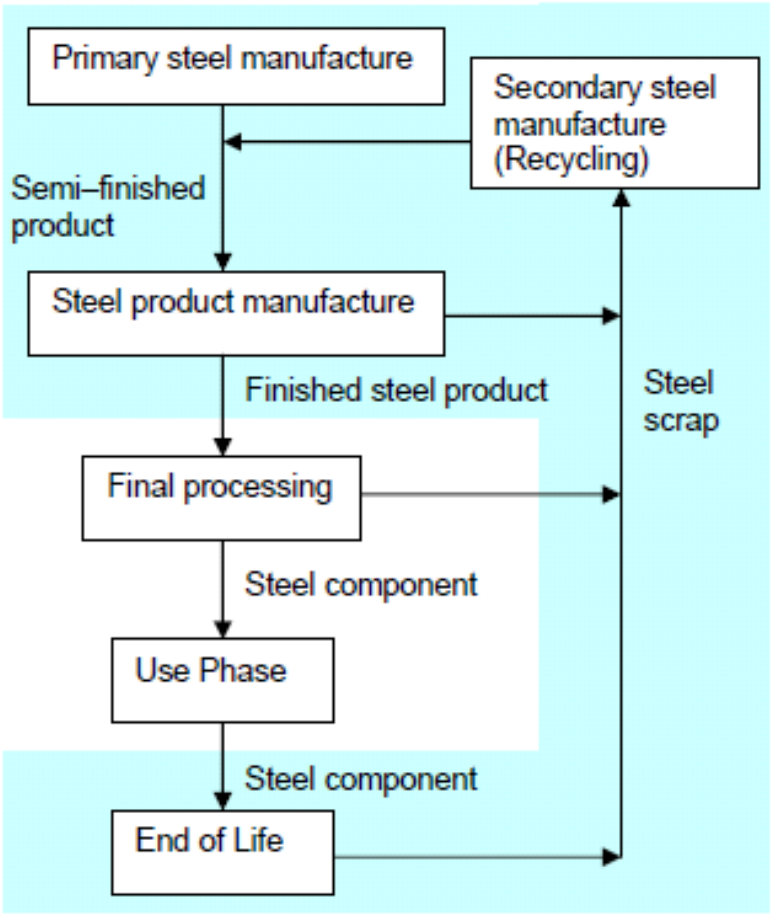
Life Cycle Inventory (LCI) Model (3)

Step 3.1- Specific sub-assemblies for P-P Baseline Assembly	**Constituent elements** (products/processes/materials)
1. Footings and exterior wall foundation (for concrete structures)	Concrete; Reinforcing steel
2. Precast concrete (conventional panel)	Precast panel Insulation (climate dependent) Steel Studs Gypsum bard Backer rod Sealant Water repellent exterior coating Latex primer and paint
3. Windows (not curtain wall)	Aluminum extrusions; Glass (low-e coating) Sealant and gaskets; Steel fasteners and anchors
4. Precast concrete beams and columns	Beams; Columns; Fasteners/anchors
5. Hollow-core floors	Hollow-core floors, 200 mm, includes steel; Topping slab, 50 mm; Shrinkage control steel
6. Elevator and stairwell walls (all concrete buildings)	Concrete; Reinforcing steel

Life Cycle Inventory (LCI) Model (4)

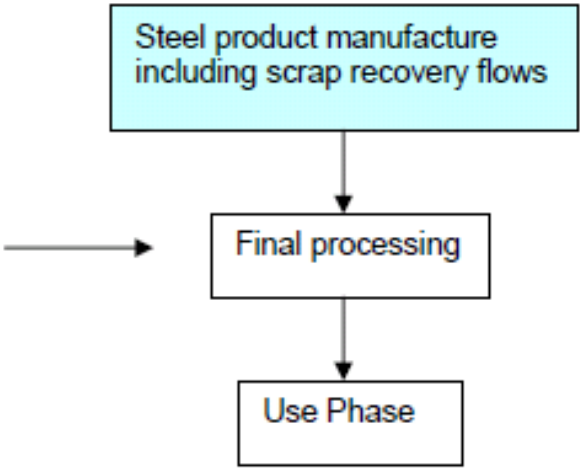
Step 3.2- Basic sub-assemblies	**Constituent elements** (products/processes/materials)
1. Interior partition walls (same for all structural systems)	Steel studs Gypsum board Paint
2. Slab on ground	Concrete Reinforcing steel Under slab vapor retarder Extruded polystyrene insulation (Toronto only)
3. Steel stairs with concrete topping	Concrete Reinforcing steel
4. Roof waterproofing system	Vapor retarder Rigid insulation Cover board Base ply membrane Cap ply membrane
5. On-site processes	All on-site construction processes

Allocation rules for Steel and Al products (1)



Source: World Steel Association. 2008.

LCA model using aggregated data

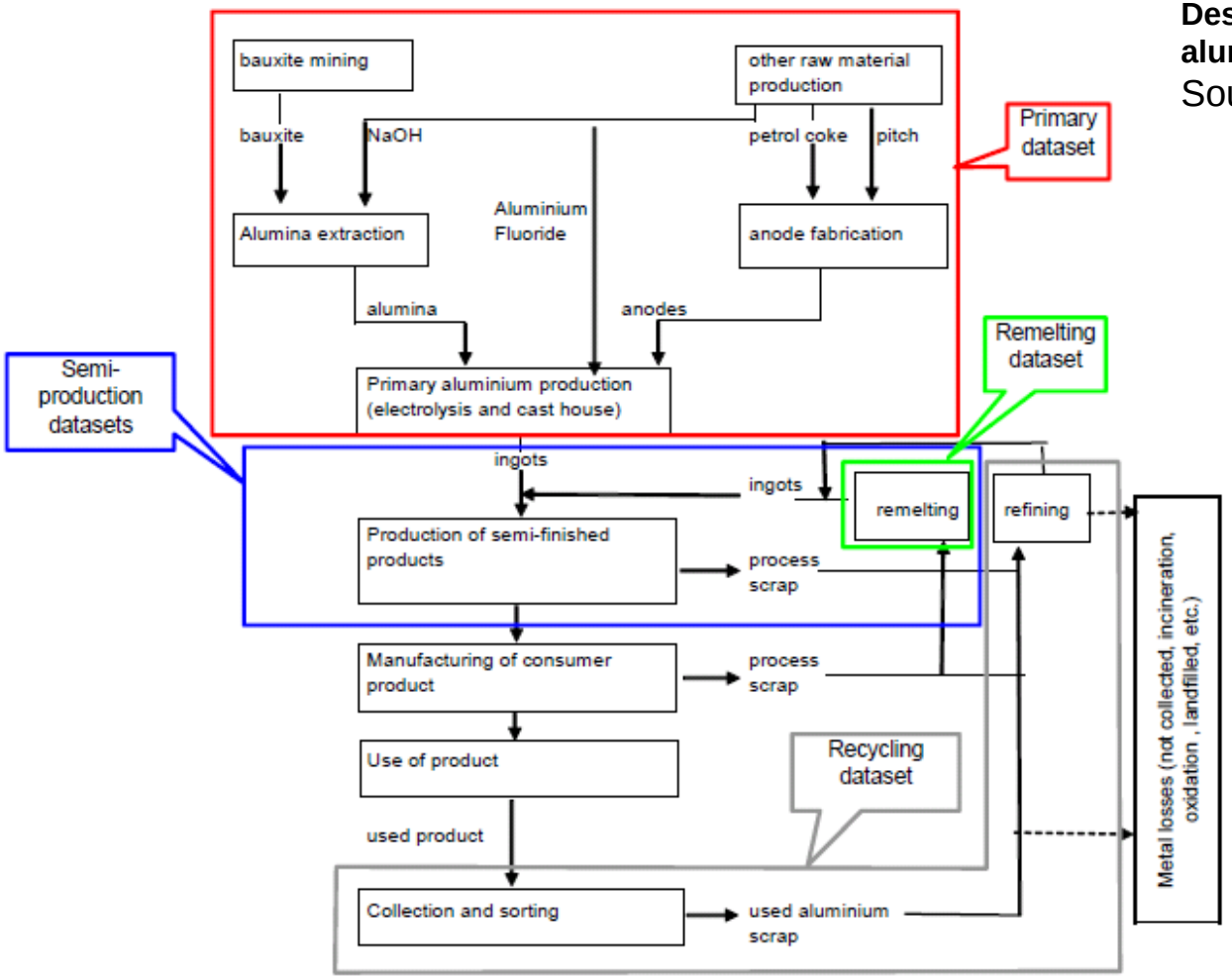


Close-loop recycling approach

A 98% and 70% recycling rate respectively for structural and reinforcement steel products is applied as per US SRI 2011 data, for the reference year 2009.

This project is using peer-reviewed LCI data on primary and secondary steel and aluminum production- Source: World Steel Association 2008 data and publications.

Allocation rules for Steel and Al products (2)



Description of the primary and secondary aluminum production.
Source: EAA 2008

A 95% recovery rate is applied for aluminum products used in North American construction sector as per IAI 2006 publication.

Close-loop recycling approach

This project is using peer-reviewed LCI data on primary and secondary steel and aluminum production- Source: International Aluminum Institute (IAI 2005) and European Aluminum Association (EAA) 2008 data and publications.

Allocation rules for Precast Concrete and Cast-in-Place products (3)

Close-loop recycling approach has been used to address the small amounts of on-site generated concrete material (the so-called “waste”), which is 100% crushed and avoids the coarse aggregate extraction and transportation at the plant gate.

The environmental load of the precast concrete and cast-in-place products is calculated by applying the following formula:

$$P = A + I – D$$

where,

P = environmental load of the precast concrete/cast-in-place products;
A = environmental load of the “precast concrete/cast-in-place manufacturing process;
I = environmental load of the “crushing” process for the concrete “waste”;
D = environmental load of the “coarse aggregate extraction and transportation”.

Life Cycle Impact Assessment (LCIA) results

- LCIA Calculation Procedure
- Precast Products Cradle-to-Gate LCIA Results
- Cast-in-Place Products Cradle-to-Gate LCIA Results
- Baseline Building LCIA Results
- LCIA Results for All Buildings
- Operating Energy (Occupancy Stage) LCIA Results

LCIA Calculation Procedure

$$GW_{Baseline} = GW_{S1} + GW_{S2} + \ldots + GW_{S6} + GW_{B1} + GW_{B2} + \ldots + GW_{B5}$$

where,

$GW_{Baseline}$	total global warming (GW) of the ***baseline building assembly*** (in kg CO_2 eq);
$GW_{S1, S2, \ldots S6}$	total GW of the constituent *specific* sub-assemblies S1 to S6- (in kg CO_2 eq);
$GW_{B1, B2, \ldots B5}$	total GW of the constituent *basic* sub-assemblies B1 to B5- (in kg CO_2 eq).

$$GW_{Sub-assembly} = GW_{CE1} + GW_{CE2} + \ldots + GW_{CEn}$$

where,

$GW_{Sub-assembly}$	total GW of the ***sub-assembly*** (in kg CO_2 eq);
$GW_{CE1, CE2, \ldots CEn}$	total GW of the constituent element CE1 to CEn (in kg CO_2 eq);
n	total number of the constituent elements (materials, products or processes);

$$GW_{CE} = \sum_{i} GWP_{100,i} \times m_i$$

GW_{CE}	total GW of the ***constituent element*** (in kg CO_2 eq);
$GWP_{100, i}$	global warming potential for substance i integrated over 100 years;
m_i	the quantity of substance i emitted per material, product, or process.

Similar calculations are conducted with SimaPro Software to calculate the full LCIA profile of all building assemblies

LCIA results- Precast Products

Cradle-to-Gate LCIA Results* for Two Precast Product Groupings [per m3] - Canada

Impact category	Unit	Hollow-core	Precast concrete wall panel, columns, beams
Global warming	kg CO_2 eq.	482	512
Acidification	H+ moles eq.	128	136
HH criteria air-mobile	kg PM2.5 eq.	0.85	0.91
Eutrophication	kg N eq.	0.071	0.075
Photochemical smog	kg NOx eq.	0.739	0.749
Solid waste	kg	93.7	93.9
Water use	m_3	0.836	0.914
Abiotic resource depletion	kg Sb eq	2.79E-04	3.01E-04
Ozone depletion	CFC-11 eq.	4.35E-08	2.08E-07
Total primary energy	MJ	5,059.2	5,402.9
Non-renewable, fossil	MJ	4,455.0	4,772.6
Non-renewable, nuclear	MJ	274.0	289.2
Renewable (SWHG)	MJ	317.1	327.8
Renewable, biomass	MJ	13.02	13.20
Feedstock, fossil	MJ	0	0

*Includes steel reinforcement.

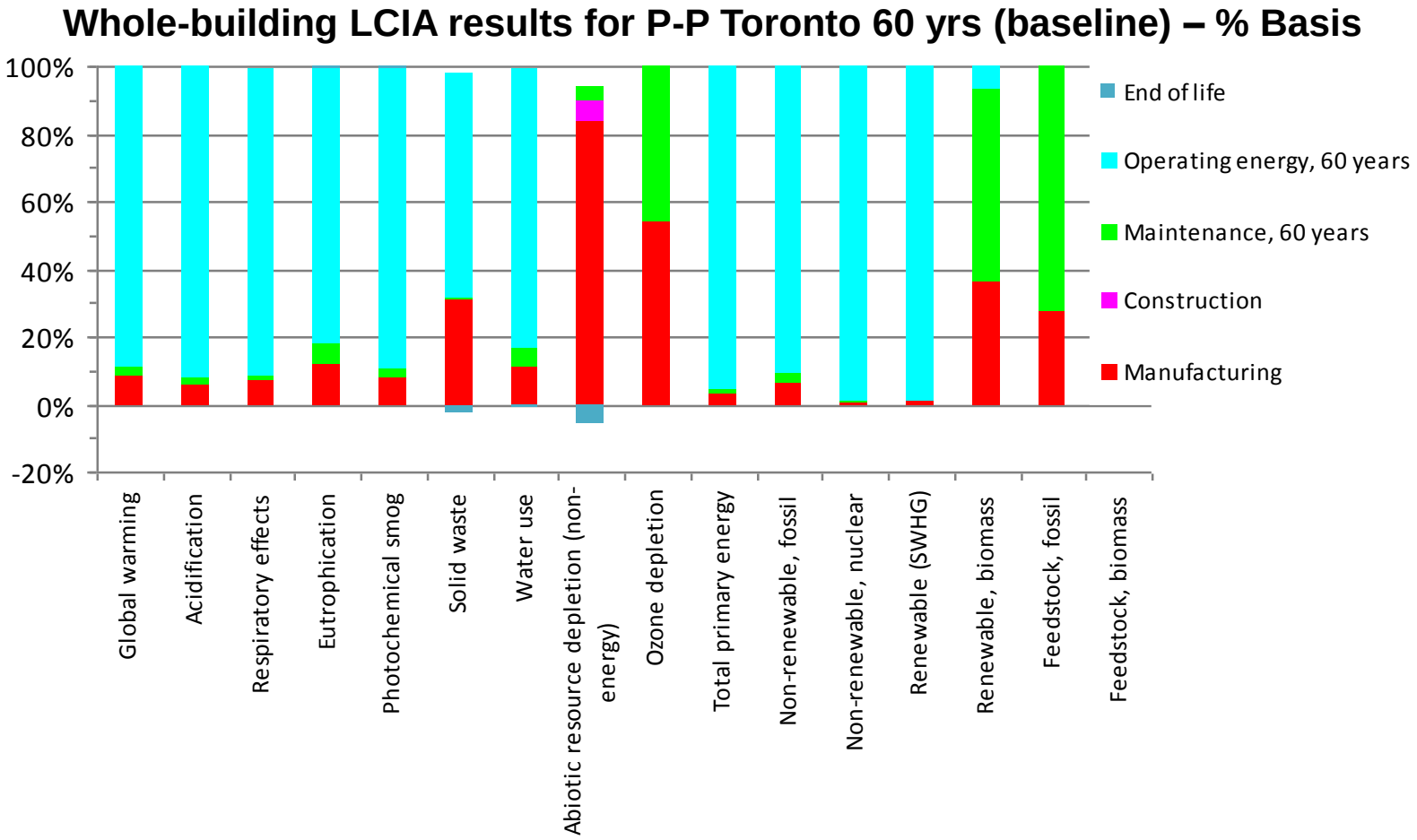
Note: HH = human health; SWHG = solar, wind, hydro and geothermal.

Cradle-to-grave LCIA results- Baseline Building- All stages (1)

Whole-Building LCIA Results for P-P Toronto 60 yrs (baseline) – Absolute Basis

Impact category	Unit	Total	Manufacturing	Construction	Maintenance	Operating energy	End of life
Global warming	kg CO_2 eq.	15,877,690	1,352,183	23,618	366,724	14,134,754	411
Acidification	H+ moles eq.	7,107,896	394,146	9,946	154,821	6,548,758	225
Respiratory effects	kg PM2.5 eq.	32,937	2,273	36	564	30,230	-165
Eutrophication	kg N eq.	2,000	231	7	122	1,621	18
Photochemical smog	kg NOx eq.	38,573	2,900	143	952	34,212	367
Solid waste	kg	601,304	194,636	274	5,324	415,797	-14,727
Water use	m^3	23,443	2,597	10	1,332	19,713	-209
Abiotic resource depletion	kg Sb eq.	1.69	1.61	0.12	0.08	0.00	-0.12
Ozone depletion	CFC-11 eq.	4.39E+00	2.36E+00	7.42E-05	2.03E+00	1.70E-04	2.93E-04
Total primary energy	MJ	547,806,690	16,292,663	463,220	6,672,793	524,402,212	-24,199
Non-renewable, fossil	MJ	226,054,198	14,349,802	351,023	6,040,502	205,278,863	34,007
Non-renewable, nuclear	MJ	279,968,285	1,557,841	97,679	335,580	278,028,590	-51,406
Renewable (SWHG)	MJ	41,499,744	300,355	14,469	101,956	41,089,772	-6,808
Renewable, biomass	MJ	75,449	27,229	48	43,178	4,986	7
Feedstock, fossil	MJ	209,013	57,436	0	151,577	0	0

Cradle-to-grave LCIA results- Baseline Building- All stages (2)

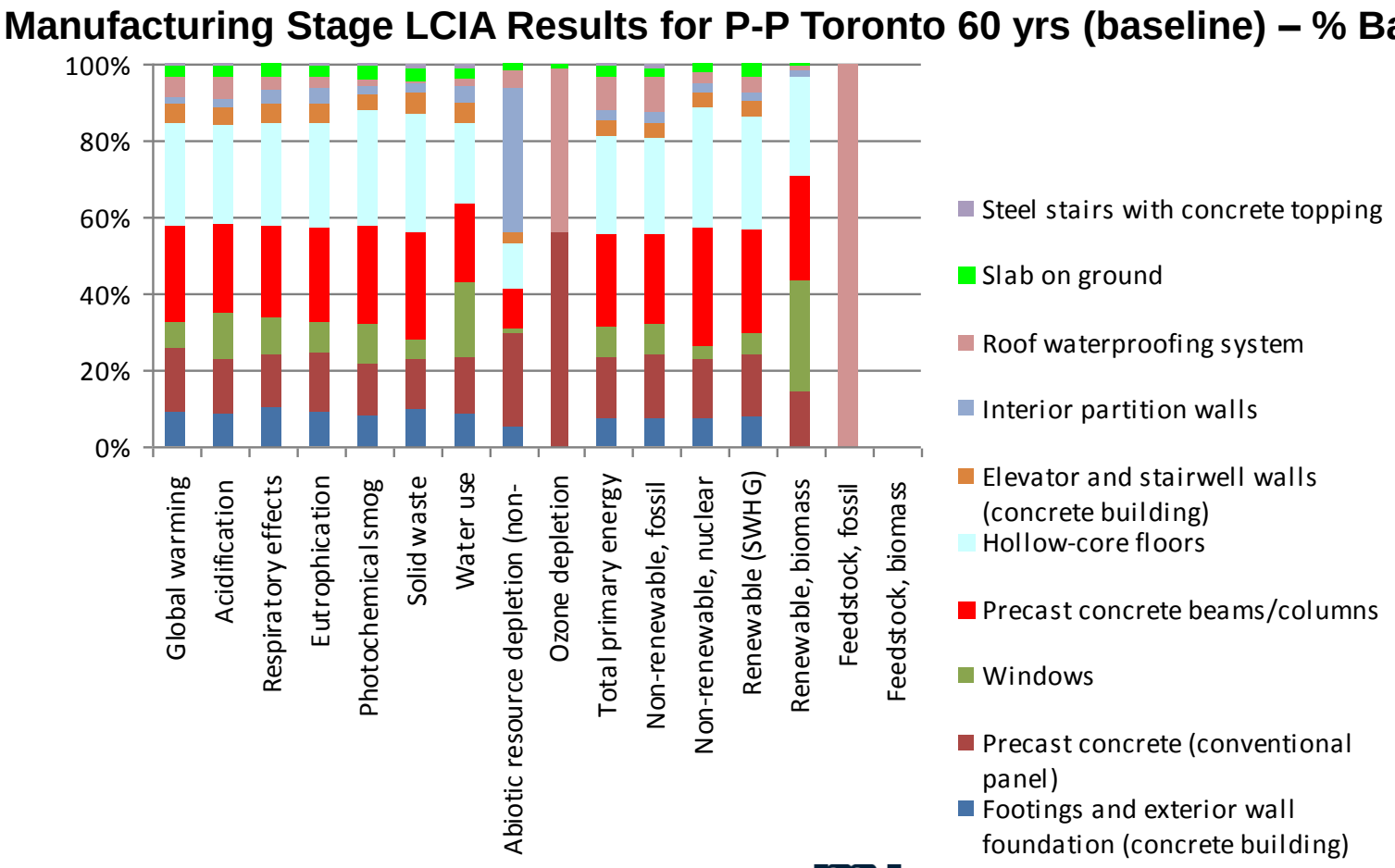


Cradle-to-construction LCIA results- Baseline Building- Manufacturing stage (1)

Manufacturing Stage LCIA Results for P-P Toronto 60 yrs (baseline) – Absolute Basis

Impact category	Unit	Total	Footings & exterior wall foundation	Precast concrete wall panel	Windows	Precast concrete beams/ columns	Hollow-core floors	Elevator & stairwell walls	Interior partition walls	Roof waterproofing system	Slab on ground	Steel stairs with concrete topping
Global warming	kg CO_2 eq.	1,352,183	125,230	221,930	92,746	337,779	365,914	66,653	29,054	67,158	37,295	8,424
Acidification	H+ moles eq.	394,146	33,353	56,281	46,706	93,378	102,048	17,423	9,753	22,163	11,156	1,884
Respiratory effects	kg PM2.5 eq.	2,273	238	311	222	541	607	123	78	70	78	4
Eutrophication	kg N eq.	231	21	36	18	57	64	11	10	6	7	1
Photochemical smog	kg NO_x eq.	2,900	240	397	299	745	866	126	67	52	91	18
Solid waste	kg	194,636	18,931	25,795	9,947	54,233	60,418	11,053	4,433	1,389	5,724	2,714
Water use	m^3	2,597	224	384	509	524	558	125	118	55	65	35
Abiotic resource depletion	kg Sb eq.	1.61	0.08	0.40	0.01	0.17	0.19	0.04	0.61	0.07	0.02	0.00
Ozone depletion	CFC-11 eq.	2.36E+00	7.10E-05	1.33E+00	5.33E-04	1.18E-04	4.52E-05	3.63E-05	5.61E-04	1.01E+00	2.62E-02	5.93E-07
Total primary energy	MJ	16,292,663	1,200,436	2,636,754	1,286,497	3,931,910	4,143,414	647,041	523,639	1,397,943	387,943	137,085
Non-renewable, fossil	MJ	14,349,802	1,061,608	2,346,287	1,200,901	3,369,462	3,554,342	576,029	474,251	1,289,886	341,982	135,054
Non-renewable, nuclear	MJ	1,557,841	114,547	238,401	60,692	474,283	493,537	58,592	41,530	38,361	36,263	1,636
Renewable (SWHG)	MJ	300,355	24,206	48,271	16,910	80,764	88,496	12,380	7,410	12,046	9,477	395
Renewable, biomass	MJ	27,229	76	3,795	7,994	7,401	7,038	39	448	214	223	1
Feedstock, fossil	MJ	57,436	0	0	0	0	0	0	0	57,436	0	0

Cradle-to-construction LCIA results- Baseline Building- Manufacturing stage (2)



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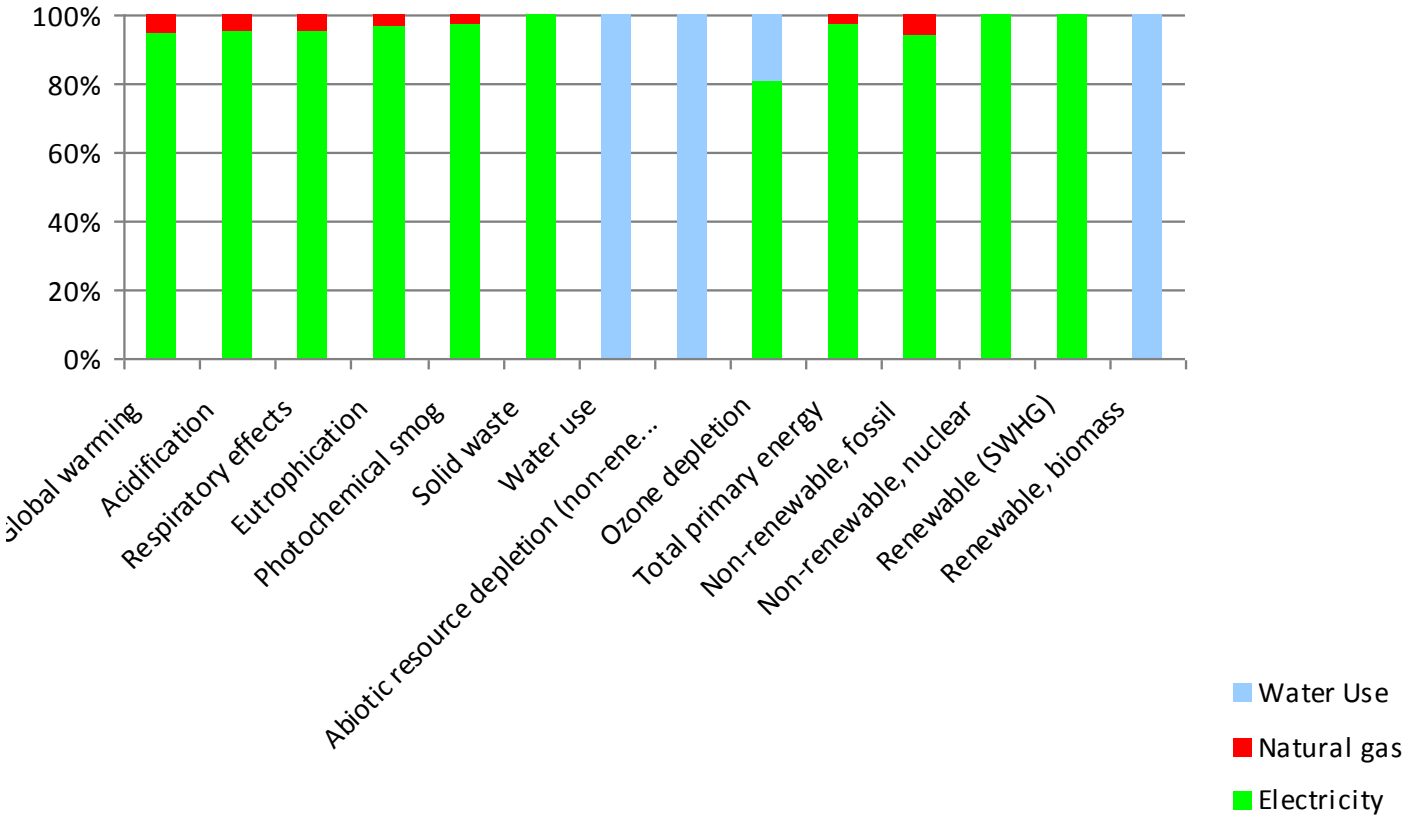
Occupancy phase LCIA results- Baseline Building- Operating energy (1)

Operating energy use LCIA results for P-P Toronto 60 yrs (baseline).



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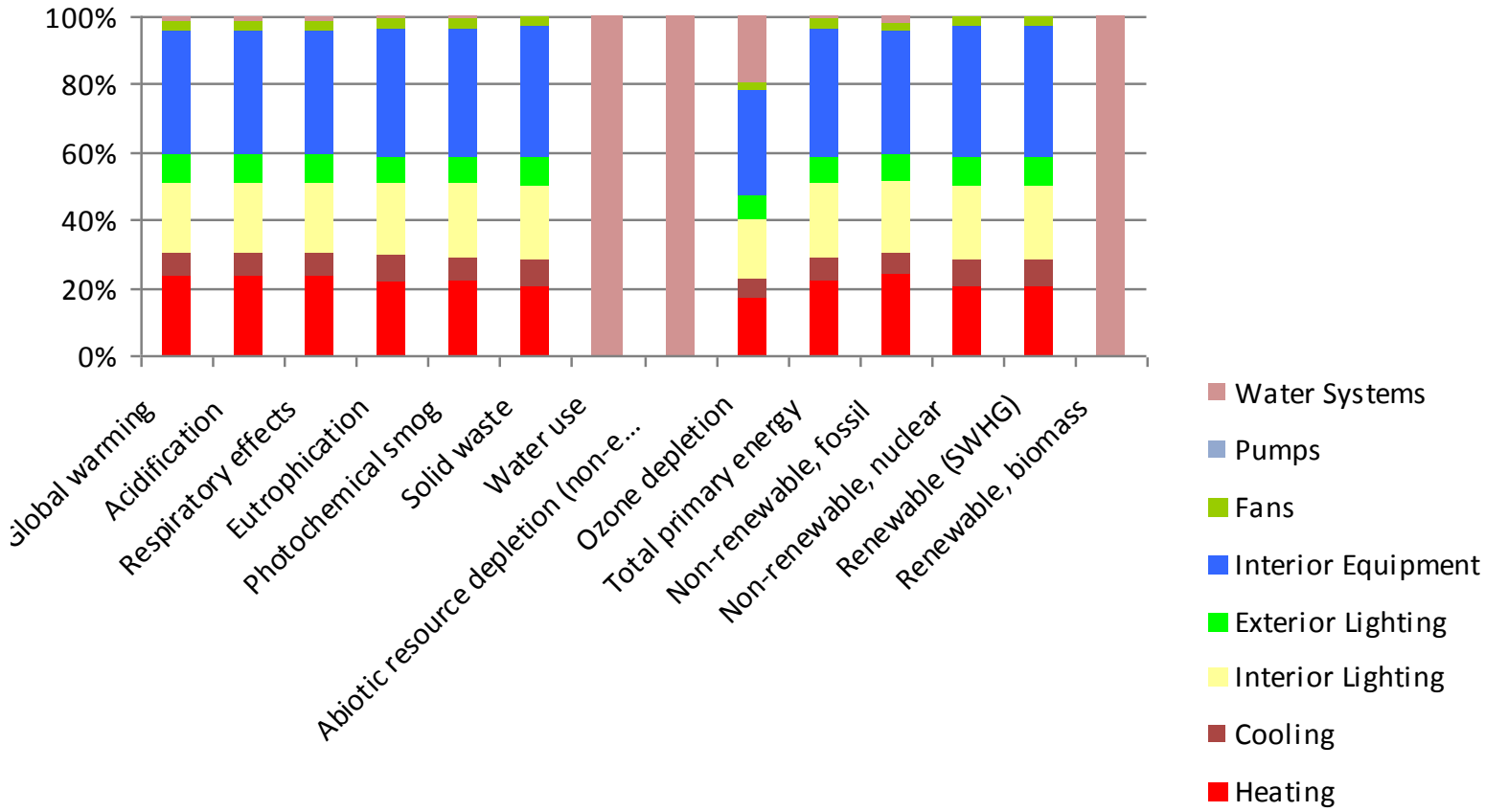
Occupancy phase LCIA results- Baseline Building- Operating energy (2)

Operating energy use LCIA results by end-use for P-P Toronto 60 yrs (baseline).



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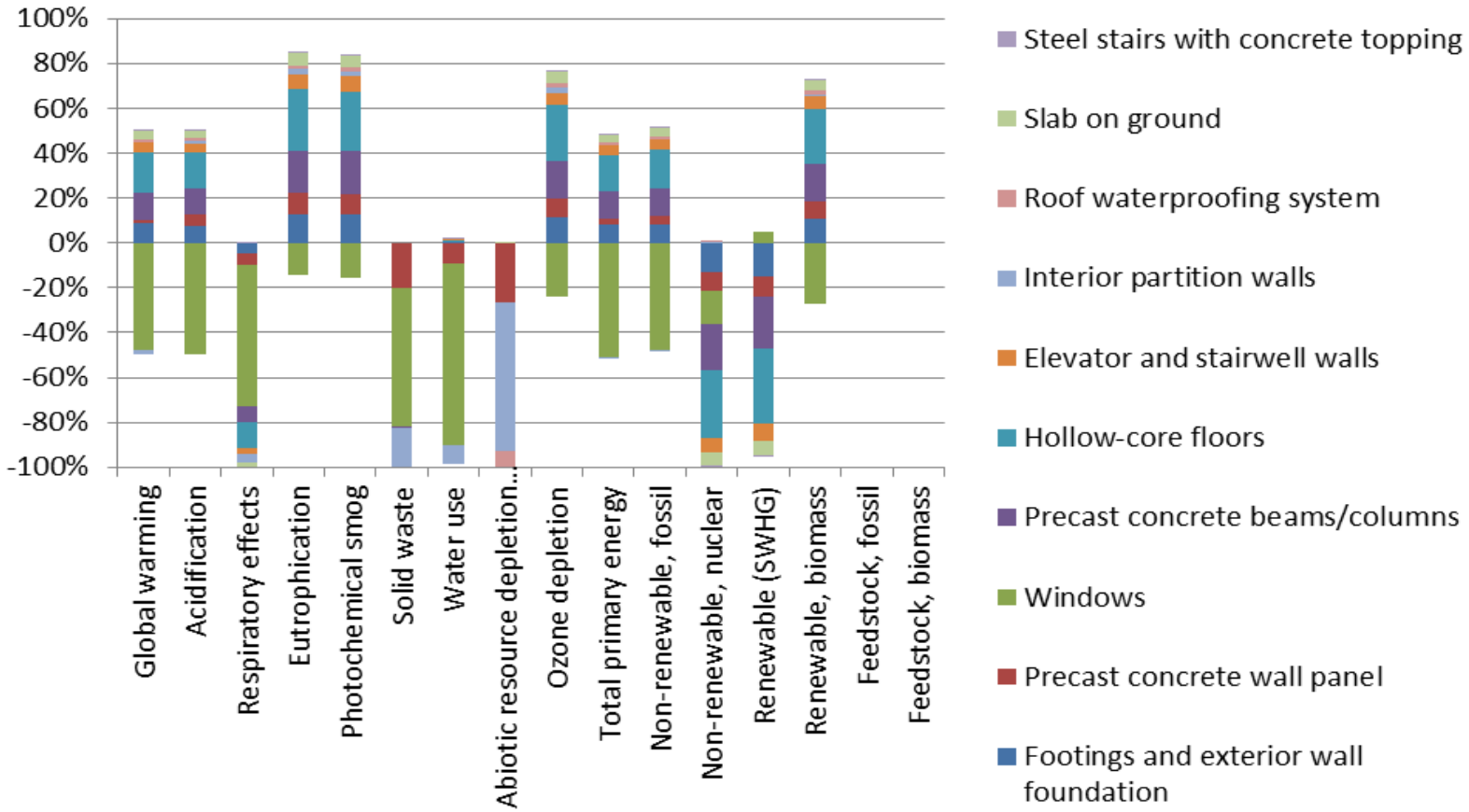
LCIA results- Baseline Building- EOL

End-of-life LCIA results for P-P Toronto 60 yrs (baseline)- absolute basis



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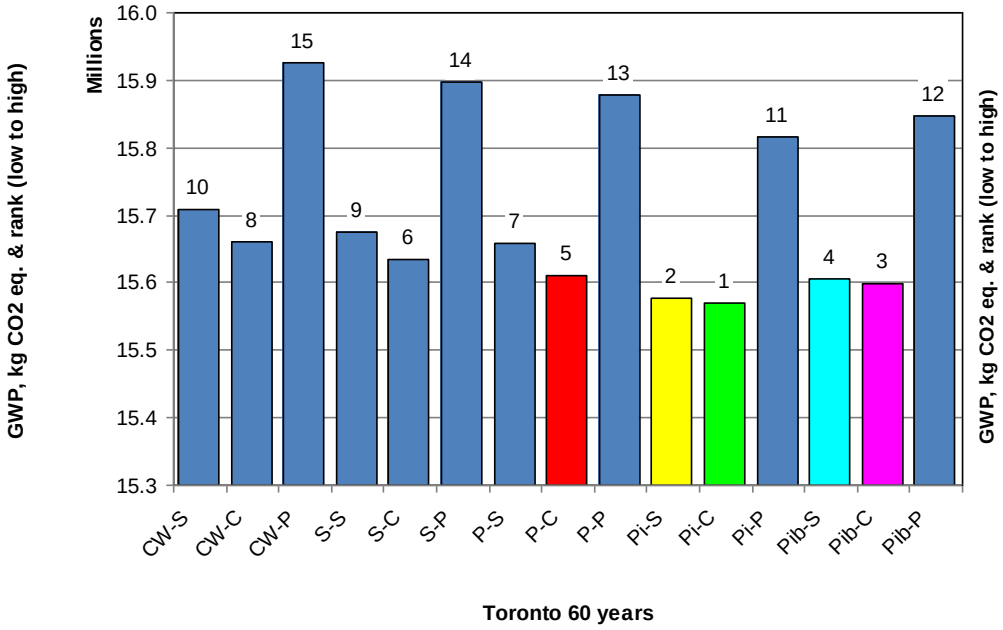
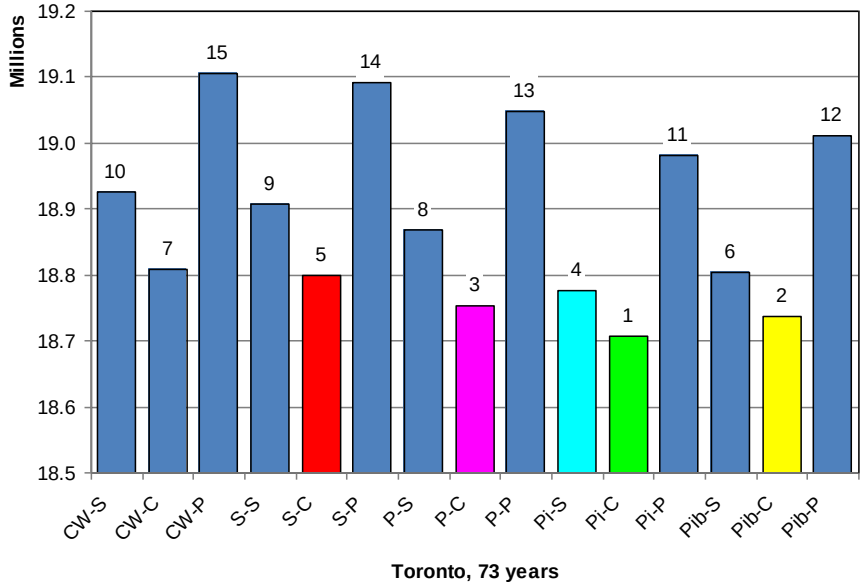
LCIA results- All Buildings- GWP-Toronto

All scenarios LCIA results: Global Warming and ranked from lowest (1) to highest (15).





1st lowest | 2nd lowest | 3rd lowest | 4th lowest | 5th lowest

60 years- Of the top 5 performers in Toronto for lowest GWP impact, all are precast wall envelopes and three have concrete structure.

73 years- Of the top 5 performers in Toronto for lowest GWP impact, four are precast wall envelopes and four have concrete structure.

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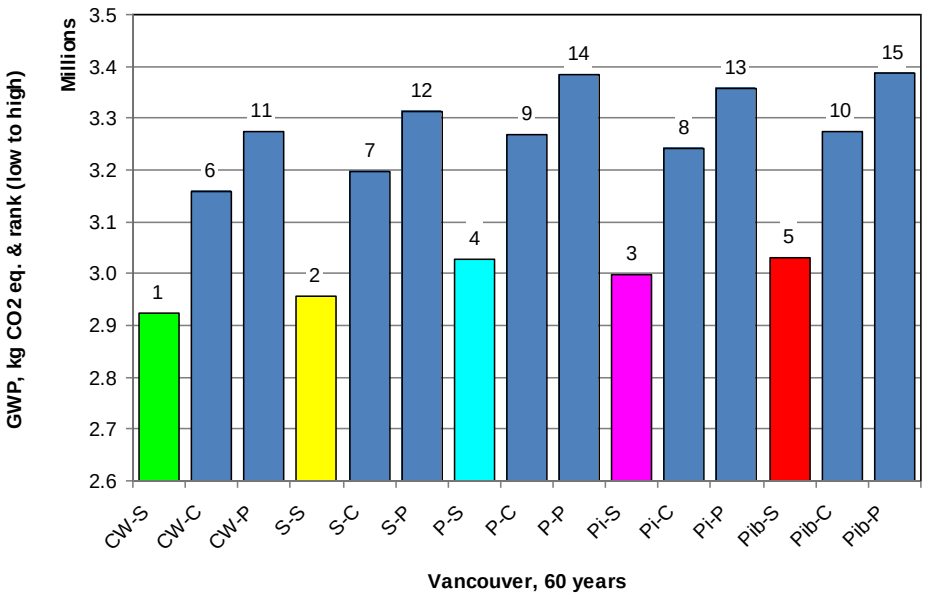
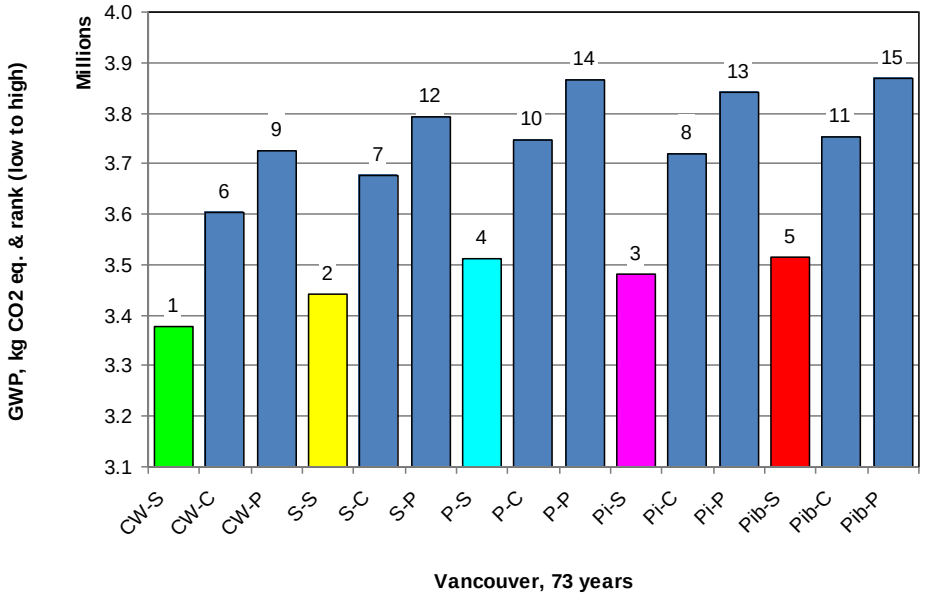
LCIA results- All Buildings-GWP-Vancouver

All scenarios LCIA results: Global Warming and ranked from lowest (1) to highest (15).





1st lowest | 2nd lowest | 3rd lowest | 4th lowest | 5th lowest

60 & 73 years- Of the top 5 performers in Vancouver for lowest GWP impact, three have precast wall envelopes, one is curtain wall and one is brick with steel stud envelope.

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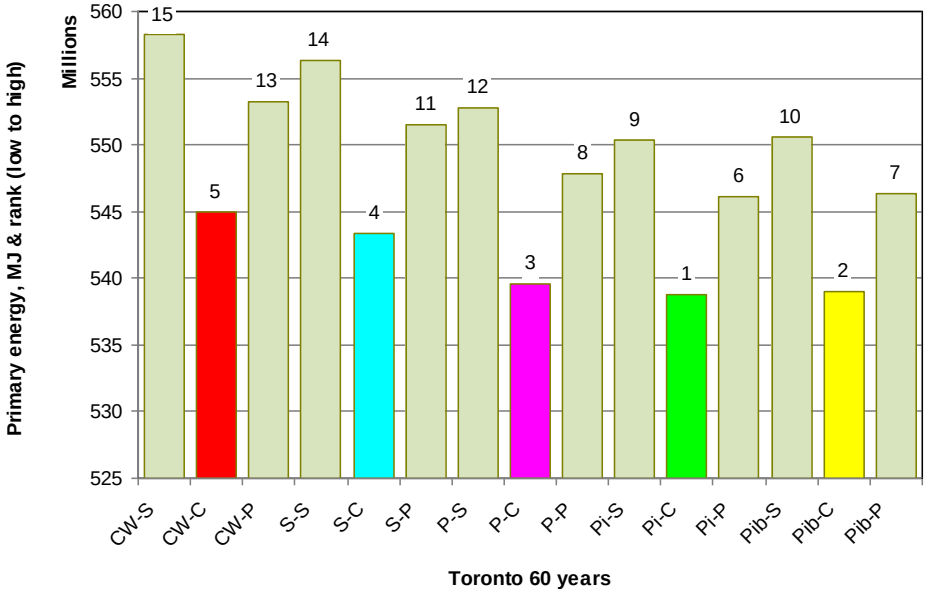
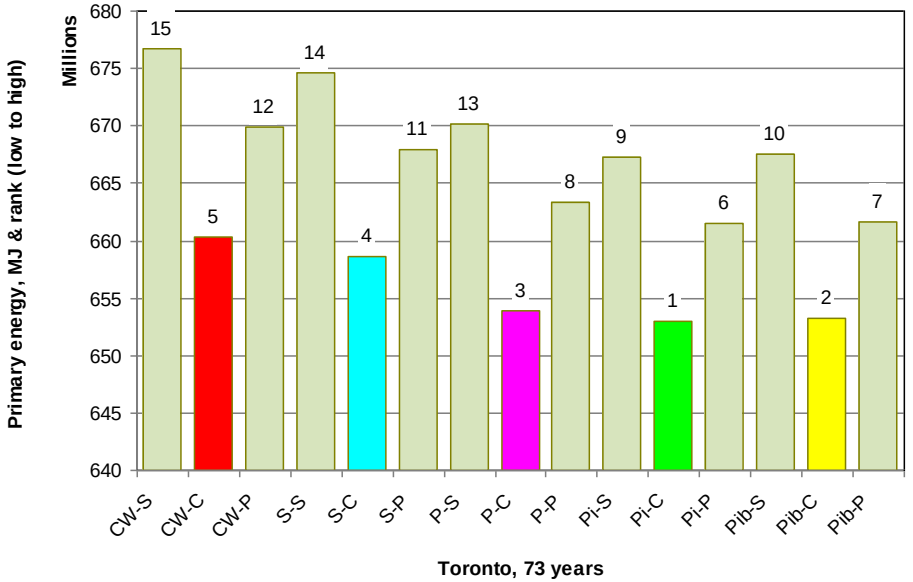
LCIA results- All Buildings-TPE-Toronto

All scenarios LCIA results: Total Primary Energy and ranked from lowest (1) to highest (15).





60 & 73 years- Of the top 5 performers in Toronto for lowest TPE impact, the top three performers are precast envelope with concrete structure and two are curtain wall, and brick and steel stud, both with concrete structure.

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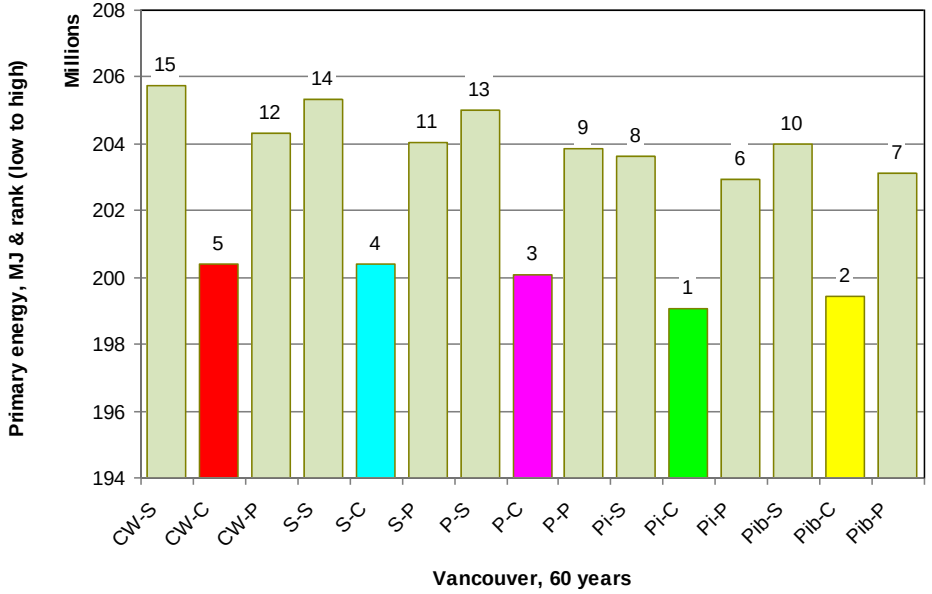
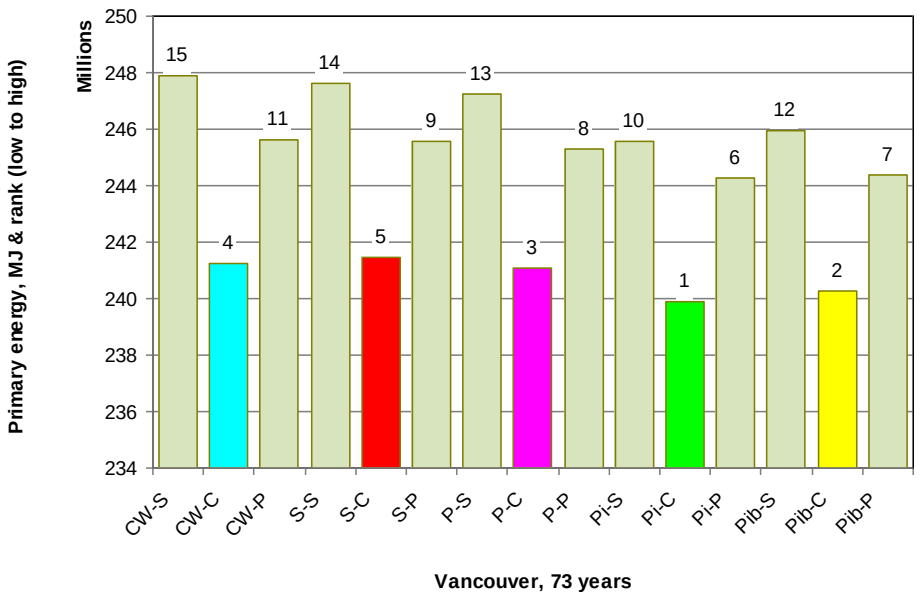
LCIA results- All Buildings-TPE-Vancouver

All scenarios LCIA results: Total Primary Energy and ranked from lowest (1) to highest (15).





60 & 73 years- Of the top 5 performers in Vancouver for lowest TPE impact, the top three performers are precast envelope with concrete structure and two are curtain wall, and brick and steel stud,with concrete structure.

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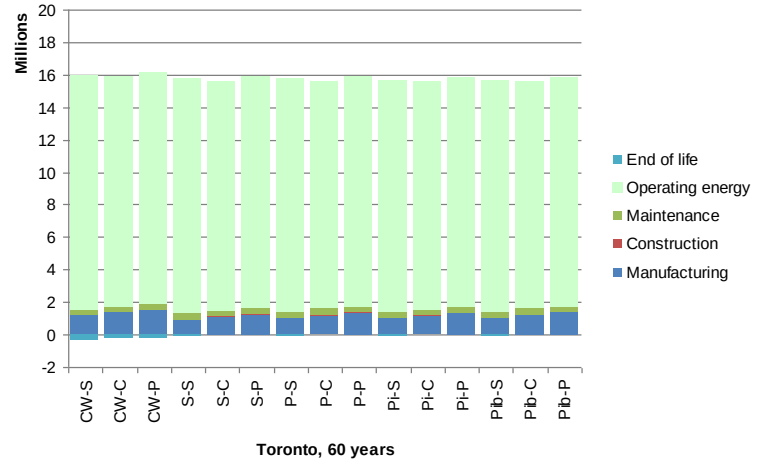
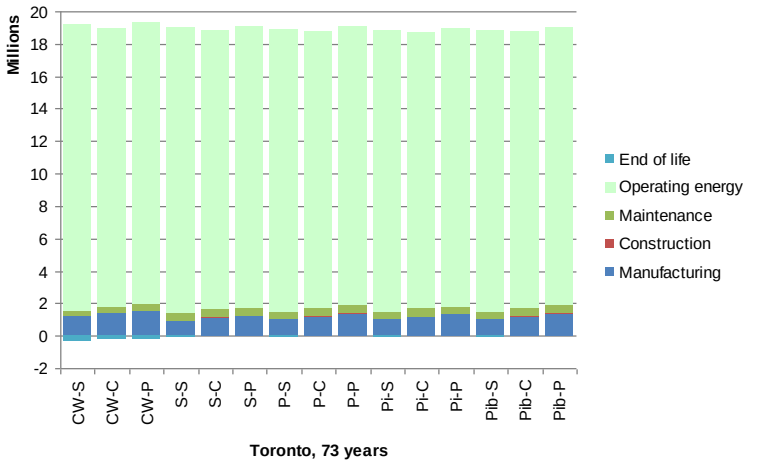
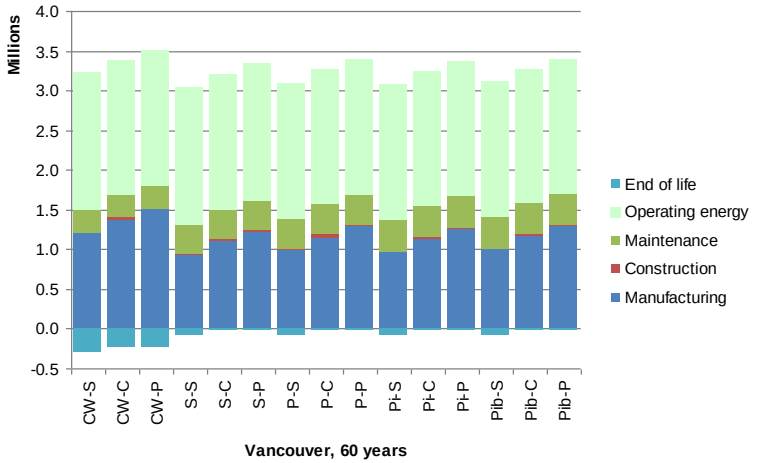
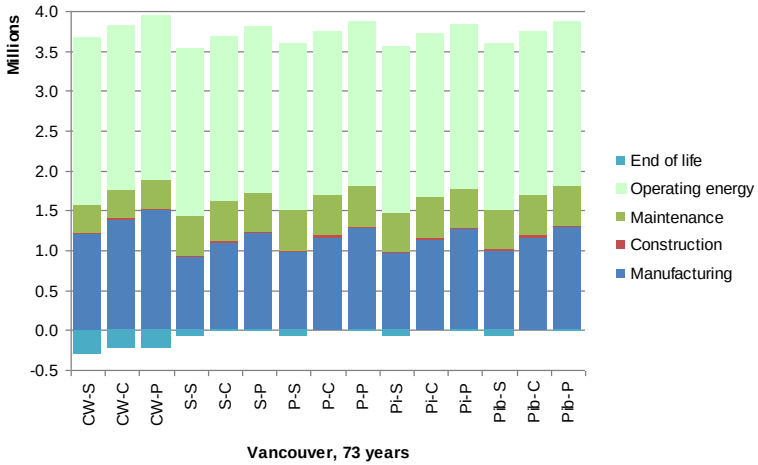
LCIA results- All Buildings by LC stage- GWP

All scenarios LCIA results by life cycle stage for global warming potential (kg CO_2 eq.)





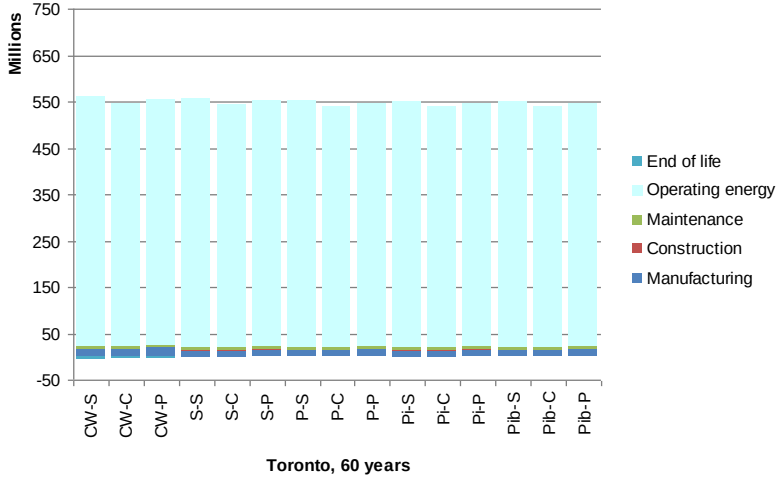




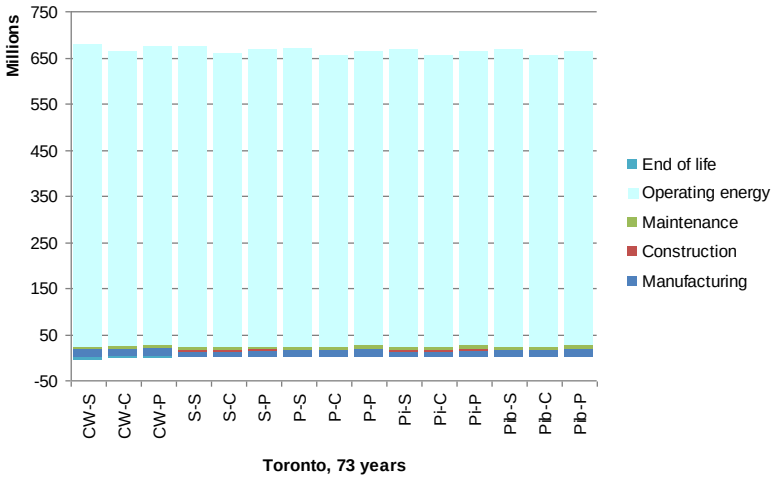
Toronto- For all building types, Operating Energy represents (89% to 93%) of the GWP impact;
Vancouver- For all building types, Operating Energy represents (50% to 62%) of the GWP impact.

LCIA results- All Buildings by LC stage- TPE

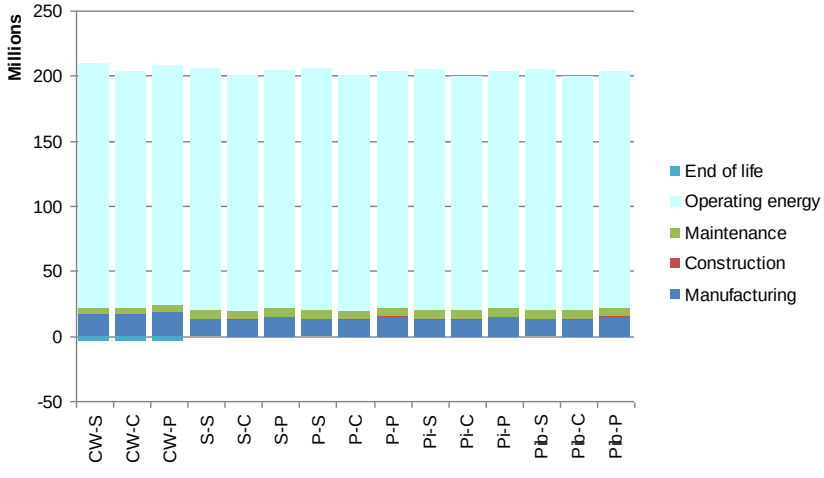
All scenarios LCIA results by life-cycle stage for total primary energy (MJ).



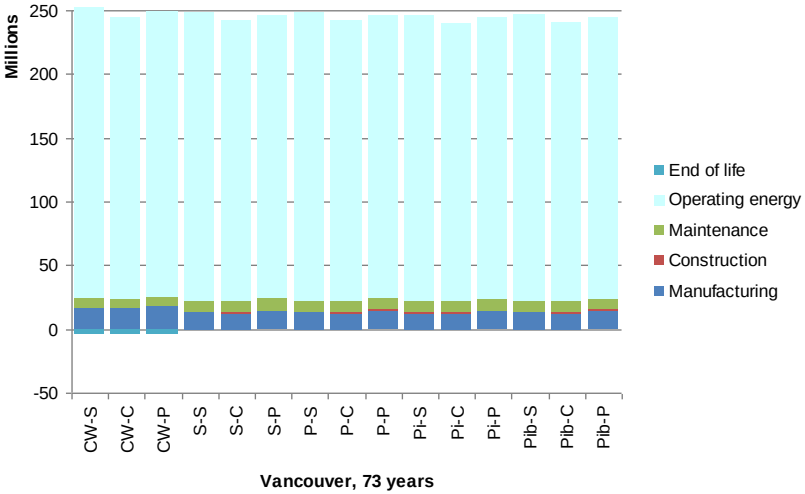
Toronto, 60 years



Toronto, 73 years



Vancouver, 60 years

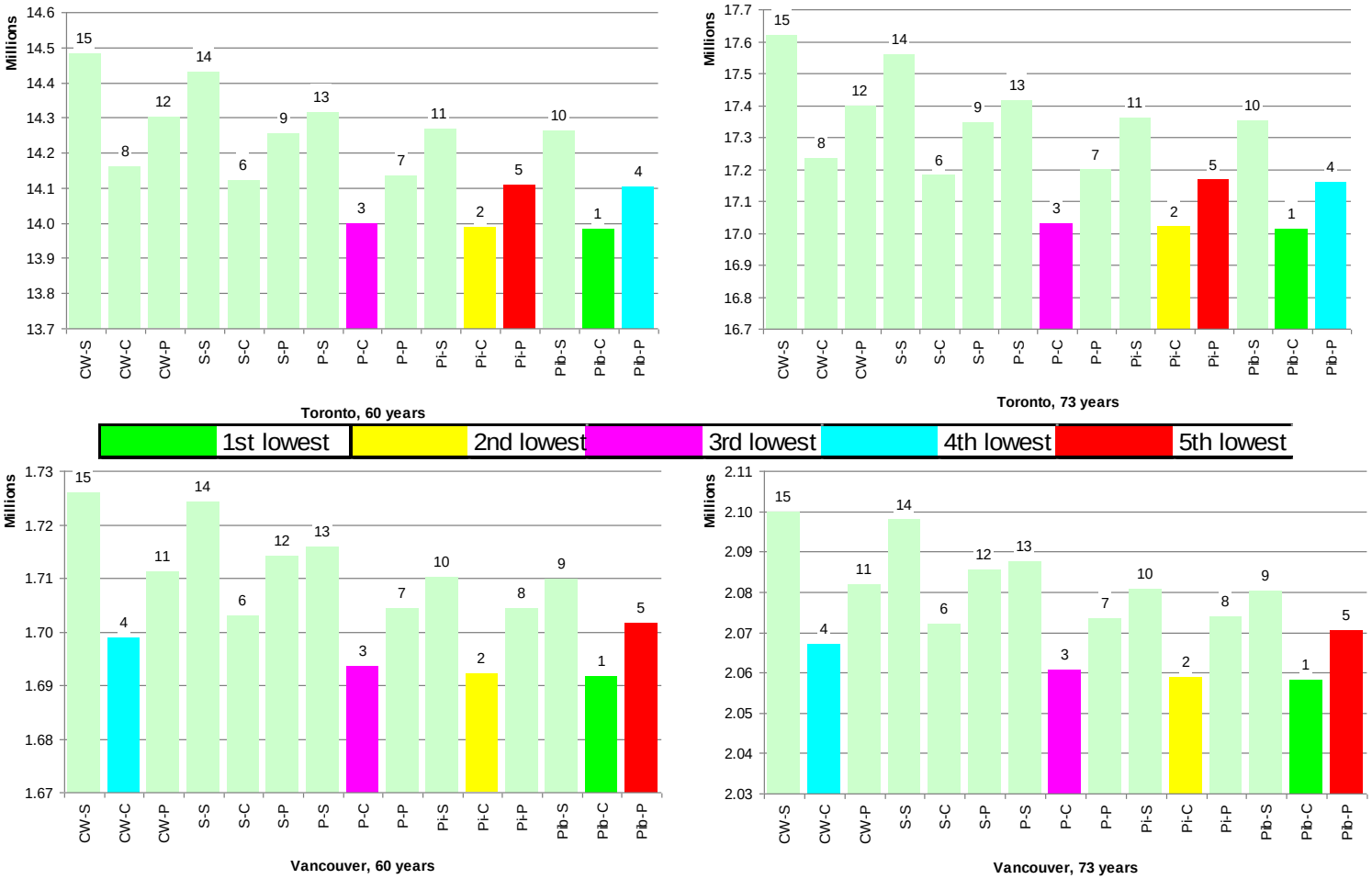


Vancouver, 73 years

Toronto- For all building types, Operating Energy represents (96% to 97%) of the TPE impact;
Vancouver- For all building types, Operating Energy represents (89% to 92%) of the TPE impact.

LCIA results- All Buildings- Operating energy- GWP

All scenarios LCIA results for GWP due to operating energy (kg CO2 eq.) and ranked from lowest (1) to highest (15)

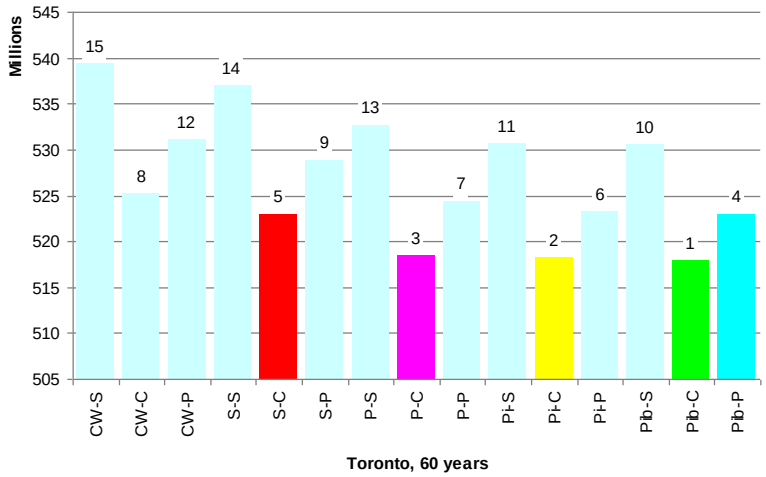


Toronto- Of the top 5 performers in terms of operating energy, for lowest GWP impact, all are precast envelopes with concrete or precast structure.

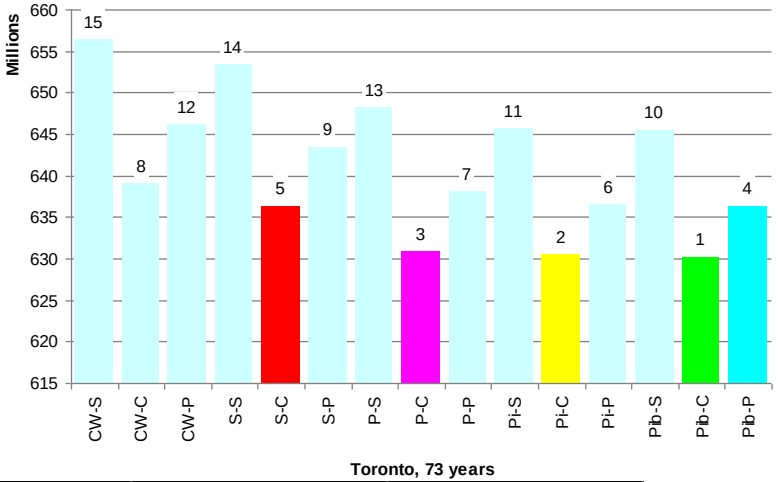
Vancouver- Of the top 5 performers in terms of operating energy, for lowest GWP impact, four are precast concrete with concrete or precast structure, and one is curtain wall with concrete structure.

LCIA results- All Buildings- Operating energy- TPE

All scenarios LCIA results for TPE (MJ) due to operating energy and ranked from lowest (1) to highest (15).

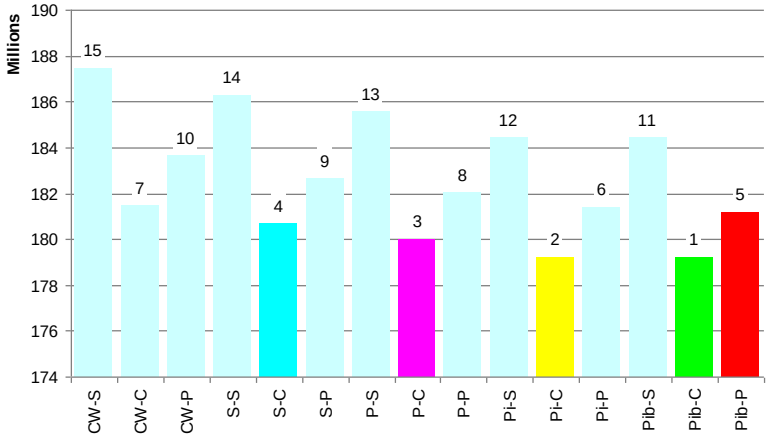


Toronto, 60 years

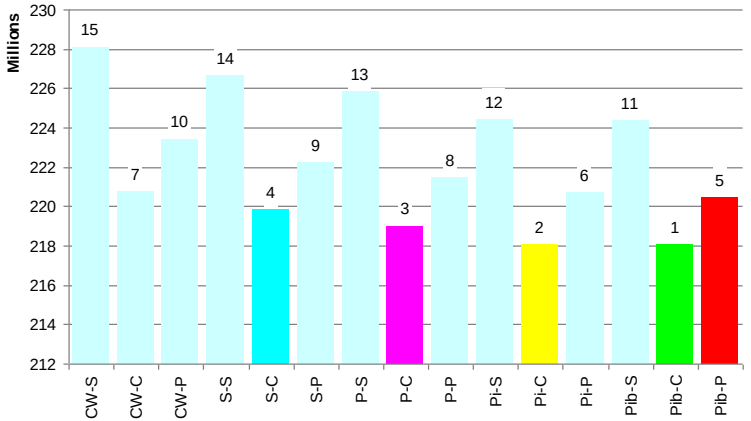


Toronto, 73 years

1st lowest | 2nd lowest | 3rd lowest | 4th lowest | 5th lowest



Vancouver, 60 years



Vancouver, 73 years

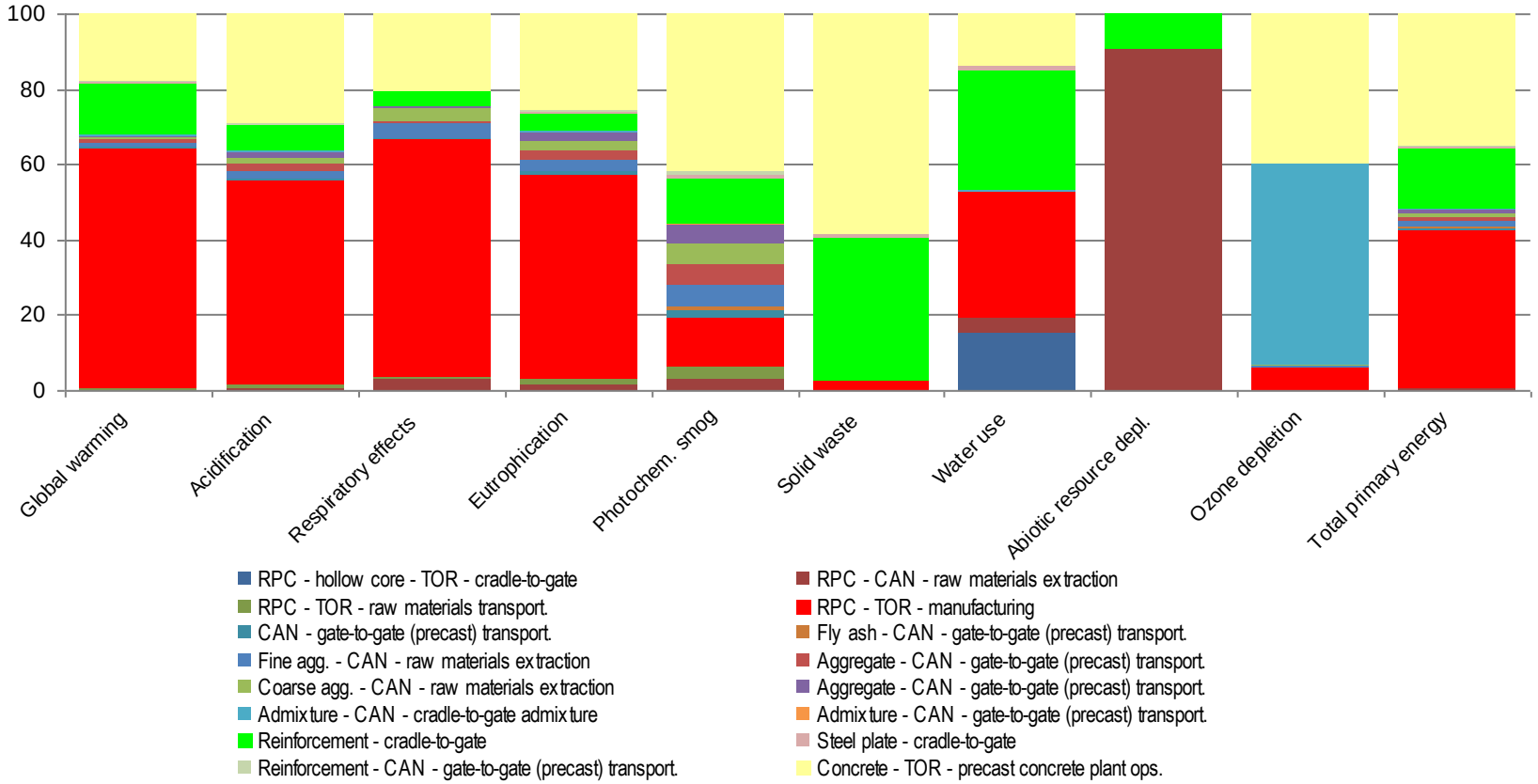
Toronto & Vancouver- Of the 5 five performers in terms of operating energy for lowest TPE impact, four are precast envelopes with concrete or precast structure, and one is brick with steel stud on concrete structure.

Interpretation phase (IP)

- Process Contribution Analysis
- Influence Analysis for Precast Products
- Sensitivity Analysis on Portland Cement Content
- Sensitivity Analysis on Thermal Performance of Exterior Walls
- Sensitivity Analysis on Recycling

IP- Process Contribution Analysis (1)

Cradle-to-gate LCIA contribution analyses of major materials and processes for m3 of precast concrete hollow-core slab (Toronto profile) – includes steel reinforcement.



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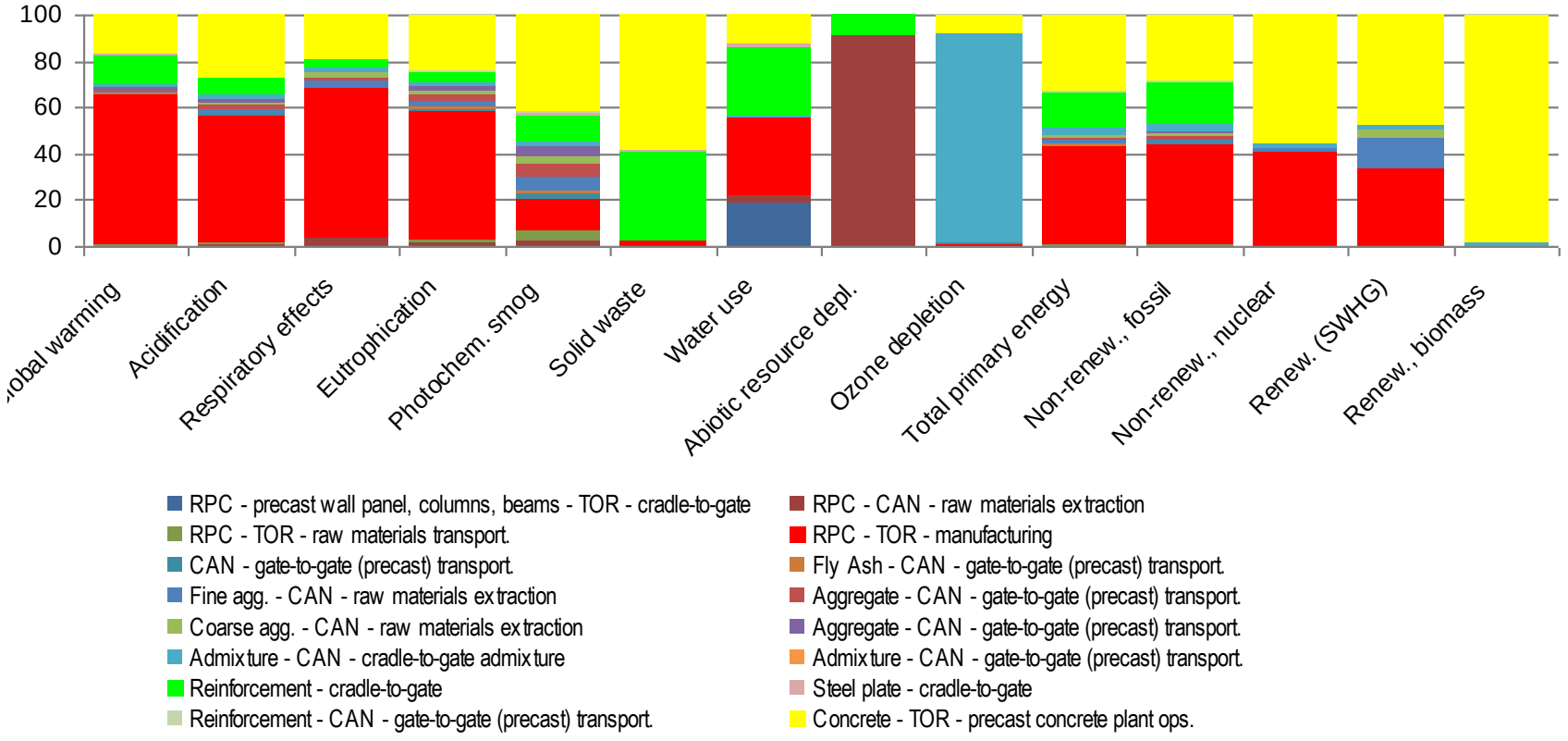
IP- Process Contribution Analysis (2)

Cradle-to-gate LCIA contribution analyses of major materials and processes for m3 of precast concrete wall panel, column and beam product grouping (Toronto profile) – includes steel reinforcement.



Athena Sustainable Materials Institute

MORRISON HERSHFIELD

IP- Influence Analysis for Precast Products

Impact category (units in % of totak)	Hollow-core - cradle-to-gate			Precast wall panel, columns, beams - cradle-to-gate		
	Plant in-house impacts	Suppliers impacts (including transport.)	Total	Plant in-house impacts	Suppliers impacts (including transport.)	Total
Global warming	17.6	82.4	100	16.6	83.4	100
Acidification	28.4	71.6	100	26.7	73.3	100
Respiratory effects	20.0	80.0	100	18.8	81.2	100
Eutrophication	25.5	74.5	100	24.2	75.8	100
Photochemical smog	41.7	58.3	100	41.1	58.9	100
Solid waste	58.8	41.2	100	58.7	41.3	100
Water use	29.0	71.0	100	30.9	69.1	100
Abiotic resource depletion	0.0	100.0	100	0.0	100.0	100
Ozone depletion	39.7	60.3	100	8.3	91.7	100
Total primary energy	33.1	66.9	100	31.0	69.0	100
Non-renewable, fossil	30.1	69.9	100	28.1	71.9	100
Non-renewable, nuclear	54.0	46.0	100	51.2	48.8	100
Renewable (SWHG)	55.5	44.5	100	53.7	46.3	100
Renewable, biomass	99.8	0.2	100	98.4	1.6	100
Feedstock, fossil	N/A	N/A	N/A	N/A	N/A	N/A

IP- Sensitivity Analysis on Portland Cement Content (1)

Based on in-depth research of the available publications in Portland Limestone Cement field [Thomas, M. et al 2010, CAC 2009a, CAC 2009b, CSA A3001-08, PCA 2003, PCA 2002] and personal communications with Canadian cement industry experts, the following assumptions are applied for the LCI modeling of general use portland limestone cement (GU PLC):

- The composition of **GU PLC** is 5% gypsum, 12% limestone, 83% clinker.
- As permitted by CSA A3001-08, one-to-one replacement basis of regular portland cement (RPC) with PLC is applied (see Slide 23);
- Water-cementitious materials ratio remains unchanged (see Slide 23);
- Percent cement substitution with SCM remains unchanged (see Slide 23).
- Density of concrete profiles remains unchanged (see Slide 23).

IP- Sensitivity Analysis on Portland Cement Content (2)

Comparison of Regular Portland Cement and Portland Limestone Cement– 1 kg

Impact category	Unit	Regular portland cement at plant	Portland limestone cement at plant	Difference, %
Global warming	kg CO_2 eq.	0.95	0.856	9.6%
Acidification	H+ moles eq.	0.219	0.199	9.3%
Respiratory effects	kg PM2.5 eq.	0.0018	0.0016	10.8%
Eutrophication	kg N eq.	0.00012	0.00011	9.3%
Photochemical smog	kg NO_x eq.	0.00044	0.00041	7.0%
Solid waste	kg	0.00646	0.00588	9.1%
Water use	m^3	0.00097	0.00088	9.8%
Abiotic resource depletion	kg Sb eq.	7.771E-07	7.770E-07	0.02%
Ozone depletion	CFC-11 eq.	7.61E-12	6.90E-12	9.4%
Total primary energy	MJ	6.621	6.022	9.0%
Non-renewable, fossil	MJ	5.957	5.401	9.3%
Non-renewable, nuclear	MJ	0.312	0.292	6.6%
Renewable (SWHG)	MJ	0.352	0.330	6.3%
Renewable, biomass	MJ	0	0	n/a
Feedstock, fossil	MJ	0	0	n/a

IP- Sensitivity Analysis on Portland Cement Content (3)

Reductions in Environmental Impact for Precast Concrete manufactured with PLC compared to Regular Portland Cement - 1m^3

Impact category	Percent reduction	
	Hollow core concrete	Precast wall panel, columns & beams
Global warming	6.1%	6.3%
Acidification	5.2%	5.3%
Respiratory effects	7.3%	7.4%
Eutrophication	5.3%	5.5%
Photochemical smog	1.4%	1.5%
Solid waste	0.2%	0.2%
Water use	3.7%	3.7%
Abiotic resource depletion	0.02%	0.02%
Ozone depletion	0.5%	0.1%
Total primary energy	3.9%	3.9%
Non-renewable, fossil	4.1%	4.1%
Non-renewable, nuclear	2.4%	2.5%
Renewable (SWHG)	2.3%	2.4%
Renewable, biomass	0	0%
Feedstock, fossil	n/a	n/a

IP- Cradle-to-Construction Sensitivity Analysis on Portland Cement Content (4)

Reductions in Environmental Impact for Buildings with Portland Cement Limestone (PLC) compared to Regular Portland Cement (RPC) – Manufacturing Stage

Impact category	Unit	Manufacturing, P-P, Vancouver				Manufacturing, P-P, Toronto			
		RPC	PLC	Difference		RPC	PLC	Difference	
				Absolute	%			Absolute	%
Global warming	kg CO_2 eq.	1,288,868	1,228,925	59,943	4.7%	1,352,183	1,290,568	61,615	4.6%
Acidification	H+ moles eq.	366,604	353,432	13,173	3.6%	394,146	380,190	13,956	3.5%
Respiratory effects	kg PM2.5 eq.	2,156	2,030	126	5.8%	2,273	2,143	129	5.7%
Eutrophication	kg N eq.	224	216	8	3.4%	231	224	8	3.4%
Photochemical smog	kg NO_x eq.	2,734	2,717	17	0.6%	2,900	2,879	21	0.7%
Solid waste	kg	192,675	192,337	339	0.2%	194,636	194,239	397	0.2%
Water use	m^3	2,586	2,522	64	2.5%	2,597	2,533	64	2.5%
Abiotic resource depletion	kg Sb eq.	2	2	0	0.0%	2	2	0	0.0%
Ozone depletion	CFC-11 eq.	2	2	0	0.0%	2	2	0	0.0%
Total primary energy	MJ	14,743,890	14,362,410	381,480	2.6%	16,292,663	15,866,453	426,210	2.6%
Non-renewable, fossil	MJ	13,519,153	13,163,063	356,090	2.6%	14,349,802	13,970,454	379,349	2.6%
Non-renewable, nuclear	MJ	247,779	246,015	1,764	0.7%	1,557,841	1,516,789	41,052	2.6%
Renewable (SWHG)	MJ	892,319	868,693	23,627	2.6%	300,355	294,545	5,809	1.9%
Renewable, biomass	MJ	27,203	27,203	0	0.0%	27,229	27,229	0	0.0%
Feedstock, fossil	MJ	57,436	57,436	0	0.0%	57,436	57,436	0	0.0%

IP- Sensitivity Analysis on Thermal Performance of Exterior Walls (1)

	Annual energy use, GJ								
Building	Base case			Sensitivity scenarios			Percent decrease		
End-use/source	Pi-S	Pi-C	Pi-P	Pi-S	Pi-C	Pi-P	Pi-S	Pi-C	Pi-P
Heating	723	680	702	674	632	652	7%	7%	7%
Cooling	206	202	202	206	202	202	0%	0%	0%
Interior lighting	610	610	610	610	610	610	0%	0%	0%
Exterior lighting	233	233	233	233	233	233	0%	0%	0%
Interior equipment	908	908	908	908	908	908	0%	0%	0%
Elevators	165	165	165	165	165	165	0%	0%	0%
Fans	79	75	76	79	74	75	1%	1%	1%
Pumps	0.4	0.4	0.4	0.4	0.4	0.4	0%	0%	0%
Water systems	58	58	58	58	58	58	0%	0%	0%
Total	**2982**	**2930**	**2954**	**2933**	**2882**	**2903**	**2%**	**2%**	**2%**
Electricity	2804	2727	2756	2758	2680	2710	2%	2%	2%
Natural gas	178	203	197	174	202	193	2%	1%	2%

This scenarios consist of adding 50 mm (2 in) of XPS insulation—RSI-1.8 (R-10)—to the existing Pi walls on three buildings in Toronto: Pi-P, Pi-C, and Pi-S, bringing the total overall effective R_{SI}-value (1/U) of the opaque portion of walls to 4.29 m2·K/W (24.4 hr·ft2·°F/Btu).

This represents an increase in overall effective wall R_{SI}-value of 61% [(4.29-2.66)/2.66].

IP- Sensitivity Analysis on Thermal Performance of Exterior Walls (2)

Sensitivity Analysis of Cradle-to-grave LCIA Results on Thermal Performance of Exterior Walls – Pi-S, Pi-C, Pi-C- 60 years –Toronto

Impact category	Unit	Absolute difference (Base case- Sensitivity case)		
		(Pi-S)	(Pi-C)	(Pi-P)
Global warming	kg CO_2 eq.	237,578	232,852	240,611
Acidification	H+ moles eq.	110,002	108,046	111,409
Respiratory effects	kg PM2.5 eq.	508	499	514
Eutrophication	kg N eq.	27	27	27
Photochemical smog	kg NO_x eq.	570	573	578
Solid waste	kg	6,886	7,066	6,977
Water use	m^3	0	0	0
Abiotic resource depletion	kg Sb eq.	0	0	0
Ozone depletion	CFC-11 eq.	0	0	0
Total primary energy	MJ	8,746,636	8,780,816	8,860,822
Non-renewable, fossil	MJ	3,461,894	3,358,092	3,505,669
Non-renewable, nuclear	MJ	4,604,299	4,724,445	4,665,643
Renewable (SWHG)	MJ	680,443	698,279	689,510
Renewable, biomass	MJ	0	0	0
Feedstock, fossil	MJ	0	0	0

This scenario represents an increase in overall effective wall R_{SI}-value of 61% [(4.29-2.66)/2.66].

IP- Sensitivity Analysis on Recycling

Cradle-to-Grave LCIA Results for Sensitivity Analysis on Recycling

Impact category	Unit	Baseline, P-P Toronto	Sensitivity, P-P Toronto	Difference, absolute
Global warming	kg CO_2 eq.	15,877,690	16,097,434	-219,744
Acidification	H+ moles eq.	7,107,896	7,192,141	-84,245
Respiratory effects	kg PM2.5 eq.	32,937	33,175	-238
Eutrophication	kg N eq.	2,000	2,087	-87
Photochemical smog	kg NO_x eq.	38,573	40,341	-1,768
Solid waste	kg	601,304	601,377	-73
Water use	m^3	23,443	23,462	-20
Abiotic resource depletion	kg Sb eq.	1.69	1.81	-0.12
Ozone depletion	CFC-11 eq.	4.39E+00	4.39E+00	-1.99E-03
Total primary energy	MJ	547,806,690	550,884,968	-3,078,278
Non-renewable, fossil	MJ	226,054,198	229,051,100	-2,996,902
Non-renewable, nuclear	MJ	279,968,285	280,042,122	-73,837
Renewable (SWHG)	MJ	41,499,744	41,507,225	-7,481
Renewable, biomass	MJ	75,449	75,507	-58
Feedstock, fossil	MJ	209,013	209,013	0

The sensitivity scenario assumes only metal products are recycled and all other materials are disposed of in landfill.

Conclusions (1)

- The **occupancy stage** (operating energy) can be responsible for up to 90% of the environmental impacts in a given impact category, but the exact amount depends on many factors, such as the severity of climate and the upstream profile of energy carriers. For example, in **Toronto**- For all building types, Operating Energy represents (89% to 93%) of the GWP impact and in **Vancouver**- For all building types, Operating Energy represents (50% to 62%) of the GWP impact.

- Through energy simulation, it was found that the interior thermal mass inherent in cast-in-place concrete and precast concrete floors (compared to concrete toppings on metal deck) reduced annual heating energy use by 6 to 15% and reduced annual energy use by 2 to 3%.

- The **cradle-to-grave global warming potential** (GWP) varies from 2,924 to 3,389 tonnes CO2 eq. for the buildings in Vancouver with 60-year service life, and 3,377 to 3,870 tonnes CO2 eq. for 73-year service life. In Toronto the range is 15,568 to 15,927 tonnes CO2 eq. for 60 years and 18,708 to 19104 tonnes CO2 eq. for 73 years.

Conclusions (2)

- **The cradle-to-grave total primary energy** varies from 119 to 205 million MJ for the buildings in Vancouver with 60-year service life, and 240 to 248 million MJ for 73-year service life. In Toronto the range is 539 to 558 million MJ for 60 years and 653 to 677 million MJ for 73 years.

- In Toronto, the buildings with the **lowest GWP** all have precast concrete envelopes and either steel or concrete structures, with the majority being concrete structure.

- In Vancouver, of the top 5 performers for **lowest GWP** impact, three have precast wall envelopes, one is curtain wall and one is brick with steel stud envelope.

- In Toronto and Vancouver, of the top 5 performers for **lowest TPE impact**, the top three performers are precast envelope with concrete structure and two are curtain wall, and brick and steel stud, both with concrete structure.

Closing Remarks & Outlook

Where do we go from here? Potential for improvement…

- LCIA Information is to be used to update the ATHENA® EcoCalculator and Impact Estimator

- The ATHENA® EcoCalculator for Assemblies provides LCA results for commonly used building structure and envelope assemblies. The results presented in the EcoCalculator are based on detailed assessments conducted using the ATHENA® Impact Estimator.

Closing Remarks & Outlook

Where do we go from here? Potential for improvement…

- The ATHENA® *Impact Estimator for Buildings* is designed to evaluate whole buildings and assemblies based on internationally recognized life cycle assessment (LCA) methodology.

- Using the *Impact Estimator*, architects, engineers and others can easily assess and compare the environmental implications of industrial, institutional, commercial and residential designs — both for new buildings and major renovations. Where relevant, the software also distinguishes between owner-occupied and rental facilities.

Closing Remarks & Outlook

Where do we go from here? Potential for improvement…

CPCI will be implementing a Green Plant Program for Precast Manufacturers:

Environmental Performance Standards

- Dust control
- Process Water, Storm Water and Chemical Management
- Noise Control

Sustainability Performance Standards

- Energy
- Materials
- Transportation

Acknowledgement (1)

LCA Project Team

- Medgar Marceau, Building Science Engineer, Morrison Hershfield *(Project Leader)*
- Dr. Lindita Bushi, Senior Research Associate, ASMI
- Jamie Meil, Managing Director, ASMI
- Matt Bowick, Research Associate, ASMI
- Wayne Trusty, Past President, ASMI
- Mark Lucuik, Building Science Specialist, Morrison Hershfield
- George J. Venta, Venta, Glaser & Associates
- Hua Sheng He, Building Science Consultant, Morrison Hershfield

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LCA Critical Review Committee

- Dr. Paulina Jaramillo, Chair, Civil and Environmental Engineering, Carnegie Mellon University
- Dr. Hafiz Elhag, British Precast Concrete Association
- Dr. Trevor Grounds, Former Chairman of the British Precast Sustainability Committee, Former Co-chair of the UK cement and concrete LCA
- Dr. Eric Masanet, Lawrence Berkeley National Laboratory

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CPCI Technical Review Committee

- Robert Burak, P. Eng., President, CPCI
- Brian J. Hall, Managing Director, Sustainability & Business Development, CPCI
- Randy Primeau, CET, LEED AP, Manager Project Management Department, The Prestressed Group
- Malcolm Hachborn, P.Eng. Chief Engineer, RES Precast Inc.

Thank you for your attention!

For more information please contact:

Commissioner

Canadian Precast/Prestressed Concrete Institute

Contact: Rob Burak, President

#100 - 196 Bronson Avenue, Ottawa, ON, K1R 6H4

Tel:(613) 232-2619; Fax:(613) 232-5139

www.cpci.ca

LCA Project Team

Athena Sustainable Materials Institute

Contact: Jamie Meil, Managing Director

119 Ross Avenue, Suite 100, Ottawa, ON, K1Y 0N6

Tel: 613.729.9996; Fax: 613.729.9997

http://www.athenasmi.org

Morrison Hershfield

Contact: Medgar Marceau, Project Leader

Suite 810, 10900 NE 8th Street, Bellevue, WA 98004

Tel: 425 289 5936; Fax: 425 289 5958

morrisonhershfield.com