40-storey Office Building Archetype Report

- Objective third-party assessment
- BIPV impact on reducing operational carbon footprint
- 15-city international report
- Contribution to supporting net zero initiatives

ClearVuePV®

ClearVue 40-Storey Archetype Office

Energy Model Report

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2024-07-02
Project: 13900-052

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Executive Summary

Footprint was engaged by ClearVue Technologies Ltd. to develop a 40-storey energy efficient archetype office model with the objective of evaluating the efficacy of selected energy strategies in pursuit of a net zero energy design.

Integral to the design is a ClearVue building integrated photovoltaic (BIPV) system. The BIPV window glazing panels are rated to generate 29 W/m^2 electricity while the opaque walls include spandrel panels with ClearVue dark glass which have a generation capacity of 200 W/m^2.

This report examines a 40-storey office building archetype energy model which has BIPV in both glazing and spandrel panels and a rooftop photovoltaic (PV) array. The report compares the energy performance of the models with 40%, 50%, 60%, and 70% window-to-wall ratios (WWR). The model presents the energy performance of a low carbon energy efficient design along with the renewable energy generation of the on-site photovoltaic arrays.

Energy modelling was used to quantify the energy consumption of the proposed design. Footprint follows a rigorous process for reviewing the building parameters, operational schedules and controls to determine total energy load, as well as renewable power generation capacity and output.

The archetype model was simulated for 15 international locations to evaluate the performance of the BIPV system and building energy use with 4 different window-to-wall ratio values in varying climate regions and under differing solar resources.

Key Findings

This report identifies the renewable output from the high-rise office building archetype with ClearVue on glazing and dark spandrel panels among 15 international cities.

It shows that BIPV helps considerably reduce both energy use intensity and greenhouse gas emissions in seeking to meet the Toronto Green Standard absolute intensity target values.

For the model with 40% WWR, buildings in 11 cities are able to achieve Net Zero or Net Positive Energy with the building mounted PV arrays. All sites had over 85% of their annual consumption generated by the building mounted photovoltaic systems.

As the window-to-wall ratio of the buildings was increased, the area of the higher W/m^2 BIPV spandrel panel was offset by glazing reducing the overall building renewable generation while the building cooling load increased. However, even at 70% window-to-wall ratio, all locations of the Archetype 40 story model had more than 50% of their annual energy generated by the building mounted PV arrays.

The emissions savings by the PV systems varied with the jurisdiction emissions factor as well as with the location solar resource but ranged up to over 1,500 to 1,600 tonnes of CO_{2e} (43 kg-CO_{2e}/m^2 of gross floor area) in regions with high solar availability and higher emissions factors.

footprint

About us

Footprint is a consulting practice comprised of a highly-specialized team of professionals dedicated entirely to sustainability.

The Footprint team draws extensively from our technical background on a diverse range of projects – many of which are leading national examples of sustainable design. Our team has earned the trust of public and private clients across Canada, and we consider it our responsibility to provide reliable and unparalleled service through every stage of a project. A proud member of the Smith + Andersen Group of Companies, Footprint's foundations lie in technical expertise gained from a proven consulting engineering firm.

Taking a more integrated approach to sustainability services, we work side-by-side with project teams, providing an informed perspective of sustainable opportunities and considerations for design and construction decisions.

Our goal is to act as a catalyst for balance – to ask the right questions and provide possible solutions that point in the right direction. How do we know what the right direction is? It's always the direction that points toward less energy, less time, less impact, and more sustainable developments. Our core services include energy engineering, energy simulation and renewable technology analysis.

Introduction

Project Description

The archetype office is developed as a 36,800 m² forty-storey office building. The building is envisioned with a high thermal performance envelope, with heat recovery and a low carbon mechanical system.

Energy Modelling

Energy modelling is much more than a mathematical representation of a building's energy performance. Properly executed, an energy model is a powerful tool that can empower decision-making processes. Whether driven by cost, emission reduction goals or energy savings, an energy model can be leveraged to analyse potential design options that yield insights that go beyond the minimum project's requirements, allowing owners and stakeholders to make informed decisions with confidence.

An energy model includes physical and operational characteristics, such as building envelope assemblies, occupancy patterns, weather data, lighting systems, and equipment specifications. Energy modelling scopes can vary depending on the project needs and goals, and are defined within the assessment methodology.

Historically, building codes have enforced energy efficiency requirements through comparative models, where compliance was determined by achieving a specified percentage of savings in comparison to a similar building with prescriptive performance for multiple parameters.

As energy modelling tools and computational capacity have advanced, certain jurisdictions have transitioned into setting absolute targets. This shift has allowed the implementation of tiered systems, incentivising higher levels of energy efficiency through tax deductions or financial incentives for meeting higher targets.

The most common targets for absolute models are:

- EUI (Energy Use Intensity) – total energy consumption relative to the building floor area. It is typically expressed as kWh/m² per year. EUI allows for the comparison of energy performance across different buildings regardless of their size or occupancy. Lower EUI values indicate higher energy efficiency.

- TEDI (Thermal Energy Demand Intensity) – similar metric to EUI, but focusing only on the thermal energy requirements for heating and cooling purposes. This incentivises the building to be optimised directly to heating and cooling demands, which may not be prioritised under conventional economic criteria. This metric is also expressed as kWh/m² per year. Lower TEDI values also indicate higher energy efficiency.

- GHGI (Greenhouse Gas Emissions Intensity) – total greenhouse gas emissions associated with the building operational energy consumption relative to its floor area. It is typically expressed as kg-CO_{2e}/m² per year. Similar to EUI, GHGI allows for the comparison of operational carbon emissions across different buildings regardless of their size or occupancy. Lower GHGI values indicate lower operational carbon emissions.

Operational Emissions

Carbon emissions can be classified into two categories, embodied and operational carbon. Embodied carbon addresses greenhouse gas emissions prior to occupancy, including harvest, extraction, manufacturing, transportation, construction, operation, demolition, and disposal.

Operational carbon is the carbon released during the occupancy and management stages of the building, including process loads, heating and cooling, ventilation, and lighting.

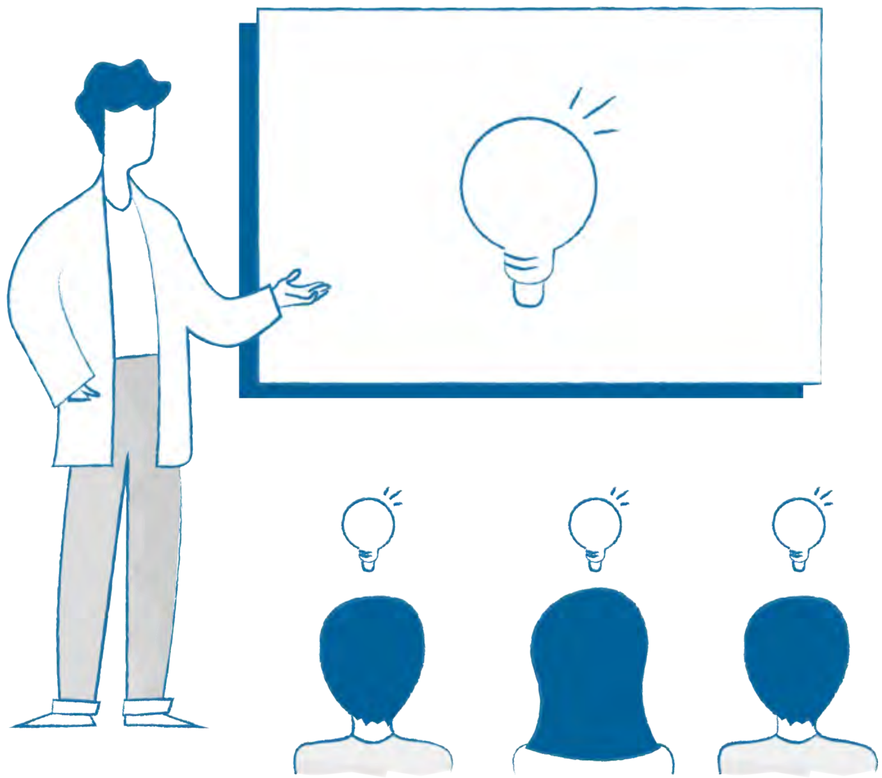
Embodied carbon is static, and operational carbon continues increasing during the lifetime of the building. It is important to address both categories of carbon emissions to achieve the Paris Agreement goals.

Net Zero

With more significant concern about climate change and its impact on resiliency, the concept of “Net Zero” has become increasingly popular. In a nutshell, it means that a building produces as much as it consumes over the course of a year. Initially it was only about energy, but over time it has been applied to water, waste, and carbon.

In most cases, the building is still reliant on municipal services. For example, a building with photovoltaic (PV) panels likely generates more electricity over summer, where it can sell it to the grid, and consumes it back during winter. A Net Zero Energy building generates the equivalent of its annual energy consumption through on-site renewable energy generation.

For Net Zero Carbon, it is best to focus on reducing emissions through decarbonisation: phasing out fossil fuel equipment, address refrigerants, reduce operational emissions for existing building and incorporating embodied carbon in the design of new buildings. The remaining emissions can be compensated through carbon removal or carbon offsets.



Methodology

The analysis of the building's energy consumption and subsequent report was completed using eQUEST DOE 2.3 build 7175. The energy simulation program complies with ASHRAE Standard 140.

The simulation model complies with the City of Toronto Energy Efficiency Report Submission & Modelling Guidelines and ANSI/ASHRAE/IESNA Standard 90.1-2013 as modified by SB-10 2017 Division 3 Chapter 2.

Scope

The scope of work includes the development of an energy model of a representative archetype multi-story office building. The building has typical energy end use profiles and building systems and components that represents a code compliant building design. The report includes energy consumption and carbon emissions. Footprint evaluated the energy performance and the renewable energy production towards a net zero development in Toronto and in 14 other cities around the world to compare energy loads and renewable production.

Proposed Design

An energy model was developed for a 36,800 m², forty-storey office building. Building floorplate dimensions were adopted from a recent project providing a 920 m² floor plate with a 2.75 ratio of east-west building length to north-south length as shown in Figure 1.

Opaque envelope components included a good, representative thermal performance roof and good wall thermal resistance including thermal bridging. The glazing is per the ClearVue specifications. For Toronto, vacuum insulated glass was modelled to reduce conduction heat loss through the building windows.

ClearVue BIPV dark glass was modelled for opaque walls while ClearVue glazing was modelled for the window area. A roof-mounted PV array was also added but the small roof area made this array capacity relatively small in comparison with the vertical PV arrays

A low carbon mechanical system was modelled – predicated on a jurisdiction where the electrical grid emission factor is relatively low. This includes optimised ventilation heat recovery, high efficiency chillers with magnetic bearings, a heat recovery chiller for climates with heating loads. Hydronic heating is provided first by an air-to-water heat pump with an electric boiler providing supplementary heating for very low ambient temperatures (below -15°C). Air handling systems are variable air volume with variable frequency drives for air volume control.

Standard design values were used for temperature setpoints, occupancy schedules, equipment and process load, lighting power density and domestic hot water demand per ASHRAE Standard 90.1-2013.

The performance of the 40 story archetype was evaluated against the Toronto Green Standard (version 4) which has targets for offices for annual heating intensity, overall energy use intensity and greenhouse gas emissions intensity.

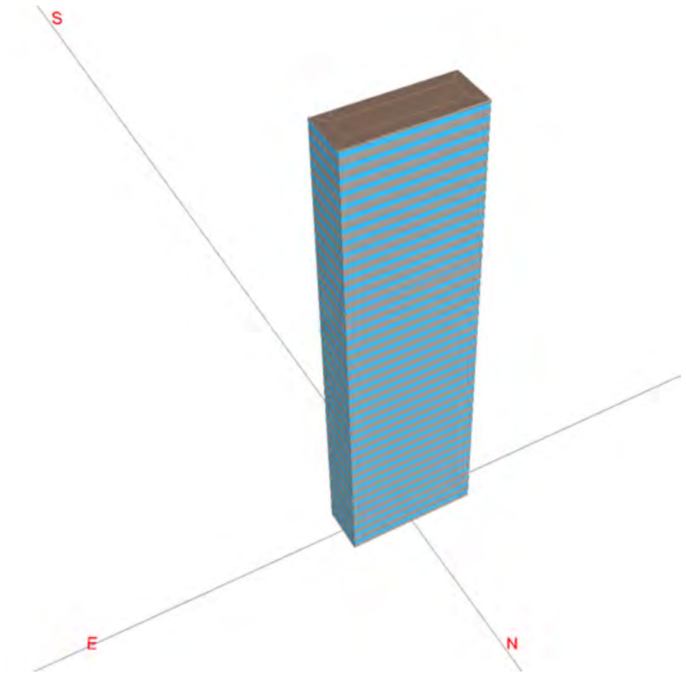


Figure 1: Archetype forty-storey office building schematic image

International Design

In addition to simulating the archetype model for the Toronto climate data, 14 other cities were selected across 6 different countries.

The cities in different hemispheres and with significantly different climates provide a demonstration of how geography and climate impact the building energy performance and the performance of the renewable generation systems.

A typical meteorological year (TMY) is a weather data set of hourly climate parameters including temperature, humidity, wind speed and direction and solar radiation data. Fifteen to thirty years of historical data is analyzed and the most representative months within the historical data are compiled to form a most representative historical year. With climate change, shorter historical periods better represent current weather and near future projections. For Toronto, the Canadian Weather Year for Energy Calculation (CWEC) 2020 City Centre was used. For the other cities, a typical meteorological year based on the historical data between 2007-2021 was used for the simulations. The weather data source for all sites was: climate.onebuilding.org.

Table 1: Tested cities and the corresponding weather files

Location	TMY Weather File
Toronto, Canada	CAN_ON_TORONTO-CITY-CENTRE_6158359_CWEC2020.bin
Canberra, Australia	AUS_ACT_Canberra.Intl.AP.949260_TMYx.2007-2021.bin
Sydney, Australia	AUS_NSW_Sydney.Intl.AP.947670_TMYx.2007-2021.bin
Darwin, Australia	AUS_NT_Darwin.Intl.AP.941200_TMYx.2007-2021.bin
Brisbane, Australia	AUS_QLD_Brisbane-Archerfield.AP.945750_TMYx.2007-2021.bin
Adelaide, Australia	AUS_SA_Adelaide.Intl.AP.946720_TMYx.2007-2021.bin
Hobart, Australia	AUS_TAS_Hobart.Intl.AP.949750_TMYx.2007-2021.bin
Melbourne, Australia	AUS_VIC_Melbourne.Intl.AP.948660_TMYx.2007-2021.bin
Perth, Australia	AUS_WA_Perth.Intl.AP.946100_TMYx.2007-2021.bin
London, UK	GBR_ENG_London-Heathrow.Intl.AP.037720_TMYx.2007-2021.bin
Hong Kong, China	HKG_HKI_Hong.Kong.Intl.AP.450070_TMYx.2007-2021.bin
Seoul, South Korea	KOR_SO_Seoul.WS.471080_TMYx.2007-2021.bin
Singapore, Singapore	SGP_SG_Changi.Intl.AP.486980_TMYx.2007-2021.bin
Los Angeles, USA	USA_CA_Los.Angeles.Intl.AP.722950_TMYx.2007-2021.bin
New York, USA	USA_NY_New.York-LaGuardia.AP.725030_TMYx.2007-2021.bin

For cities with high heating loads, a vacuum glazing BIPV fenestration was modelled with a whole window U-value of 0.6 W/m²-°C. The remaining sites were modelled with double-glazed, low-e fenestration with a whole window U-value of 18. W/m²-°C. For cities with high cooling loads, a low solar heat gain coefficient (SHGC) was modelled on the glazing. Singapore was modelled with a SHGC of 0.23. Sites with higher heating loads were modelled with a SHGC of 0.36 to allow more passive solar heating. The remaining sites were modelled with a SHGC of 0.29.

It was intended that the building envelope be representative of typical construction in each of the jurisdictions under consideration. As such the opaque envelope performance for the international sites were taken from the prescriptive values from the American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE) energy standard 90.1 2016 version. The envelope components in this standard are determined by climate zone. Higher climate zone numbers denote more heating degree days and higher corresponding wall and roof thermal resistance values. Table 2 below summarises the thermal characteristics of the envelopes as well as the glazing that were modelled by location.

Table 2: Selected International Cities and Glass Properties

City	Glass U-value (W/m^2-K)	Glass SHGC	Climate Zone	Wall R-value (m^2-K/W)	Roof R-value (m^2-K/W)
Canberra, Australia	1.8	0.29	4A	2.75	5.50
Sydney, Australia	1.8	0.29	3A	2.29	4.52
Darwin, Australia	1.8	0.29	0A	1.42	4.52
Brisbane, Australia	1.8	0.29	2A	1.98	4.52
Adelaide, Australia	1.8	0.29	3B	2.29	4.52
Hobart, Australia	1.8	0.29	4A	2.75	5.50
Melbourne, Australia	1.8	0.29	3A	2.29	4.52
Perth, Australia	1.8	0.29	3A	2.29	4.52
Toronto, Canada	0.6	0.36	5A	3.20	5.50
Hong Kong, China	1.8	0.29	1A	1.42	3.67
Seoul, South Korea	1.8	0.29	4A	2.75	5.50
Singapore, Singapore	1.8	0.23	0A	1.42	4.52
London, UK	0.6	0.36	4A	2.75	5.50
Los Angeles, US	1.8	0.29	3C	2.29	4.52
New York, US	0.6	0.36	4A	2.75	5.50

For the Toronto design, a window area to wall area ratio (WWR) of 40% glazing is typical. However, this was not viewed as more broadly applicable. One component of the study was to investigate differing window to wall ratios on both the energy performance and the renewable energy production of the buildings. As such, energy simulation runs for the building were under take for window to wall ratios of 40%, 50%, 60% and 70%.

Results

The objective of this study was to achieve Net Zero Energy through optimised building design, supplemented by ClearVue's BIPV products for renewable electrical generation.

The ClearVue models are achieving high energy performance on greenhouse gas emissions intensity (GHGI), Thermal Energy Demand Intensity (TEDI), and Total Energy Use Intensity (TEUI) when the WWR is set to 40%, and the energy performance decreases as the WWR increases. With the glazing and spandrel BIPV, in Toronto, the overall BIPV energy generation can fulfill 86% of the annual building energy consumption with 40% WWR.

Further details regarding the specifications about ClearVue glazing, spandrel and cladding BIPV can be found on the company's website at www.clearvuepv.com.

Projected Energy Consumption – Toronto, Canada

The Toronto Green Standard (TGS) is a standard to be met by all new developments within the City of Toronto. It includes several absolute energy and greenhouse gas emissions intensity targets for by building type. Office buildings are to meet tier 1 levels presently as shown in the table below. Tier 2 will become mandatory in 2025 and tier 3 becomes mandatory in 2028.

The energy use intensity (EUI), thermal energy demand intensity (TEDI) and greenhouse gas emissions intensity (GHGI) results for the Archetype 40-storey building simulated with the Toronto climate set including solar PV for different WWR values can be found on Table 3. Typically, increasing the window to wall ratio leads to increased heating and corresponding TEDI in the Toronto climate. In this study, this is mitigated by the excellent thermal performance of the vacuum glazing at USI 0.6 W/m^2-°C such that the increasing conduction loss over larger windows is compensated by the increased passive solar gains.

Table 3: ClearVue Archetype Office – Toronto Energy Consumption

Model	TEUI (kWh/m^2)	TEDI (kWh/m^2)	GHGI ($kg\text{-}CO_{2e}/m^2$)
TGS v4 Tier 1 Targets – Office Buildings	130	30	15
TGS v4 Tier 2 Targets – Office Buildings (2025)	100	22	8
TGS v4 Tier 3 Targets – Office Buildings (2028)	65	15	4
Archetype 40-storey – 40% WWR - Toronto	10.5	30.0	0.2
Archetype 40-storey – 50% WWR - Toronto	19.0	27.2	0.4
Archetype 40-storey – 60% WWR - Toronto	27.8	25.3	0.6
Archetype 40-storey – 70% WWR - Toronto	37.4	23.8	0.7

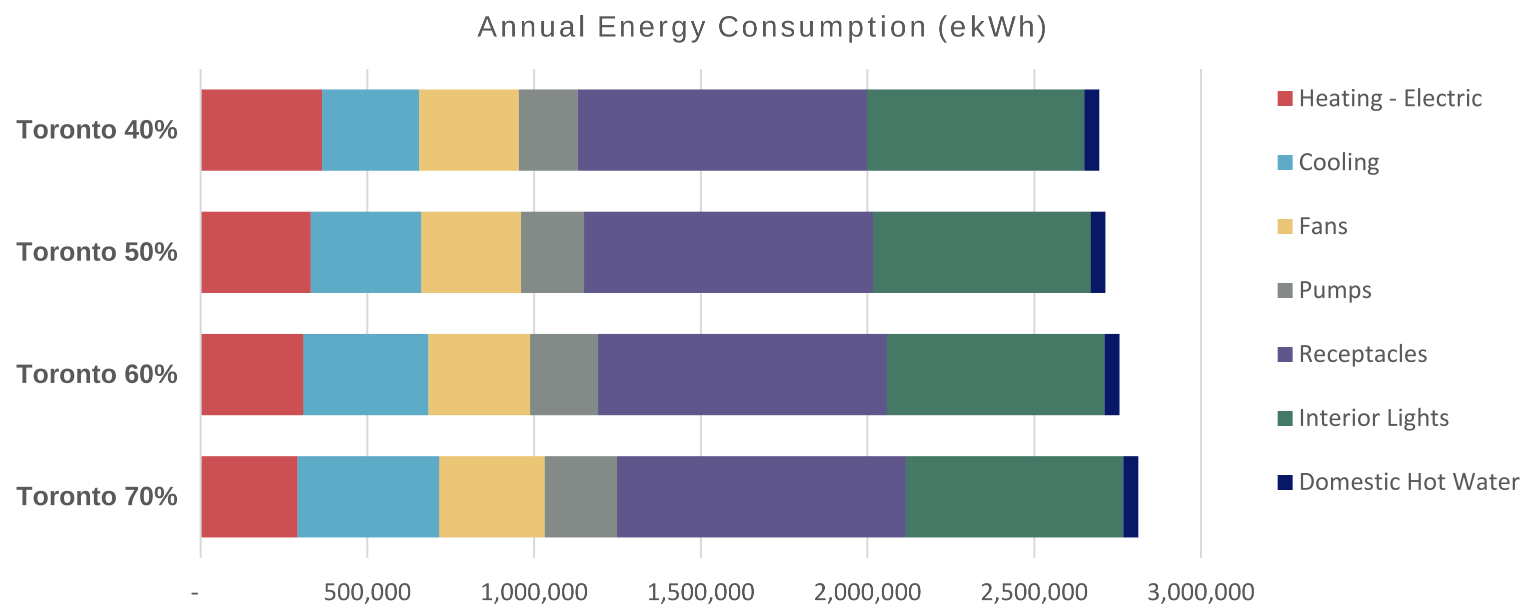
The BIPV and improved glazing are contributing to compliance with the Toronto Green Standard – especially in the overall energy use intensity and greenhouse gas intensity.

TEUI - Total energy use intensity - annual energy consumption by all end uses divided by gross modelled area.
TEDI - Thermal demand energy intensity - annual heating for envelope losses and ventilation divided by gross modelled area.
GHGI - Greenhouse gas emissions intensity - scope 1 and 2 GHG emissions for energy used on site divided by gross modelled area.

Results Breakdown for the Toronto models with all WWR

Figure 2 below illustrates the breakdown in annual energy use on an end-use basis for the ClearVue Archetype Office before the renewables are applied with all the WWR simulation runs.

Figure 2: ClearVue Archetype with 40% to 70% WWR – Annual Energy Consumption



Projected Energy Production – Toronto, Canada

ClearVue forty-storey office building with 40% WWR

As shown on Table 4, the office building in Toronto with 40% WWR delivered 86% of the building energy requirements. If achieving net zero energy for the building through on-site PV generation, then in addition to the building integrated PV arrays, a 1,372 m² array of capacity 269 kW is required for Toronto. Being the northern-most city evaluated in the study, Toronto had one of the lowest productions from the same sized PV arrays.

Table 4: ClearVue Archetype Office with 40% WWR

Array	Area (m²)	PV Capacity (kW)	Annual Generation (kWh)	kWh/kW
South Glazing BIPV	3,680	106.7	99,302	931
East Glazing BIPV	1,338	38.8	27,287	703
West Glazing BIPV	1,338	38.8	28,205	727
North Glazing BIPV	3,680	106.7	36,239	340
South Spandrel BIPV	5,520	1,104.1	1,035,607	938
East Spandrel BIPV	2,007	401.5	284,124	708
West Spandrel BIPV	2,007	401.5	293,382	731
North Spandrel BIPV	5,520	1,104.1	383,259	347
BIPV subtotal	26,930	3,302.2	2,187,405	662
Roof mounted PV	460	101.2	129,075	1,275
Total	**27,390**	3,403.4	**2,316,480**	**86%**
Ground mounted site PV to achieve net zero energy	1,372	301.8	384,942	14%

ClearVue forty-storey office building with 50% WWR

As shown on Table 5, the office building in Toronto with 50% WWR delivered 74% of the building energy requirements.

The glazing BIPV has been modelled with a capacity of 29 W/m². The spandrel BIPV has been modelled with a generation capacity of 200 W/m². As the glazing to spandrel area increases, the overall building BIPV capacity diminishes.

Table 5: ClearVue Archetype Office with 50% WWR

Array	Area (m²)	PV Capacity (kW)	Annual Generation (kWh)	kWh/kW
South Glazing BIPV	4,600	133.4	123,971	929
East Glazing BIPV	1,673	48.5	33,744	696
West Glazing BIPV	1,673	48.5	34,880	719
North Glazing BIPV	4,600	133.4	45,235	339
South Spandrel BIPV	4,600	920.1	858,619	933
East Spandrel BIPV	1,673	334.6	235,650	704
West Spandrel BIPV	1,673	334.6	243,336	727
North Spandrel BIPV	4,600	920.1	317,617	345
BIPV subtotal	25,090	2,873.2	1,893,051	659
Roof mounted PV	460	101.2	129,075	1,275
Total	**25,550**	**2,974.4**	**2,022,125**	**74%**
Ground mounted site PV to achieve net zero energy	2,494	548.6	699,709	26%

ClearVue forty-storey office building with 60% WWR

As shown on Table 6, the office building in Toronto with 60% WWR delivered 63% of the building energy requirements.

Table 6: ClearVue Archetype Office with 60% WWR

Array	Area (m²)	PV Capacity (kW)	Annual Generation (kWh)	kWh/kW
South Glazing BIPV	5,520	160.1	148,637	928
East Glazing BIPV	2,007	58.2	40,686	699
West Glazing BIPV	2,007	58.2	42,056	723
North Glazing BIPV	5,520	160.1	54,229	339
South Spandrel BIPV	3,680	736.0	690,404	938
East Spandrel BIPV	1,338	267.7	187,045	699
West Spandrel BIPV	1,338	267.7	193,157	722
North Spandrel BIPV	3,680	736.0	255,506	347
BIPV subtotal	25,090	2,444.0	1,611,721	659
Roof mounted PV	460	101.2	129,075	1,275
Total	**25,550**	**2,545.2**	**1,740,795**	**63%**
Ground mounted site PV to achieve net zero energy	3,651	803.1	1,024,289	37%

ClearVue forty-storey office building with 70% WWR

As shown on Table 7, the office building in Toronto with 70% WWR delivered 51% of the building energy requirements. This is the combined result of the increased cooling load along with the decrease in higher capacity per unit area spandrel BIPV with less opaque wall surface area.

Table 7: ClearVue Archetype Office with 70% WWR

Array	Area (m²)	PV Capacity (kW)	Annual Generation (kWh)	kWh/kW
South Glazing BIPV	5,520	186.8	173,938	931
East Glazing BIPV	2,007	67.9	47,631	701
West Glazing BIPV	2,007	67.9	49,232	725
North Glazing BIPV	5,520	186.8	63,484	340
South Spandrel BIPV	3,680	552	513,161	930
East Spandrel BIPV	1,338	200.7	138,617	691
West Spandrel BIPV	1,338	200.7	143,143	713
North Spandrel BIPV	3,680	552	189,585	343
BIPV subtotal	25,090	2014.8	1,318,790	655
Roof mounted PV	460	101.2	129,075	1,275
Total	**25,550**	**2,116**	**1,447,865**	**51%**
Ground mounted site PV to achieve net zero energy	4,901	1,078.2	1,375,116	49%

Projected Energy Consumption – International

ClearVue PV Archetype Application

Figure 3 to Figure 6 and Table 8 to Table 11 show energy by end use for the building models before PV using by city for WWR ranging from 40% to 70%. Figure 3 is for 40% WWR.

Figure 3: Annual Energy by End Use by City: Model with 40% WWR

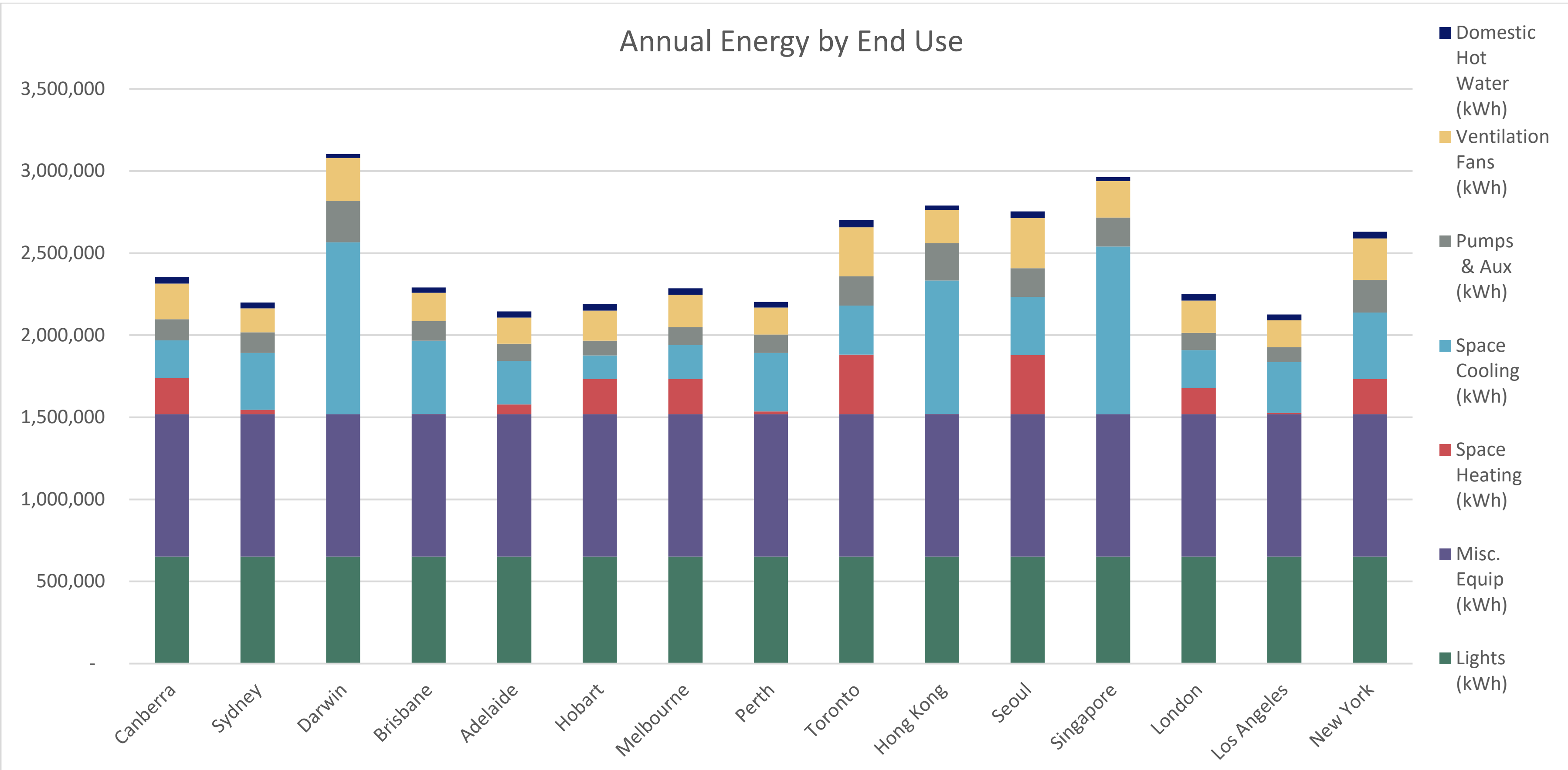


Table 8: Annual Energy By End Use by City: Model with 40% WWR

Location	Lights (kWh)	Misc. Equip (kWh)	Space Heating (kWh)	Space Cooling (kWh)	Pumps & Aux (kWh)	Ventilation Fans (kWh)	Domestic Hot Water (kWh)	Total (kWh)
Canberra, Australia	652,204	866,911	220,161	229,638	128,821	216,354	40,229	2,354,317
Sydney, Australia	652,199	866,911	26,750	345,931	125,564	146,904	34,271	2,198,530
Darwin, Australia	652,191	866,911	-	1,046,088	251,407	262,947	24,315	3,103,859
Brisbane, Australia	652,178	866,911	1,398	445,366	120,291	172,575	32,503	2,291,223
Adelaide, Australia	652,187	866,911	58,964	264,306	105,187	160,633	36,002	2,144,190
Hobart, Australia	652,215	866,911	215,076	142,447	90,117	182,503	40,564	2,189,834
Melbourne, Australia	652,210	866,911	215,190	204,764	110,216	197,132	38,711	2,285,135
Perth, Australia	652,201	866,911	16,708	356,107	111,206	165,527	34,184	2,202,844
Toronto, Canada	652,182	866,911	363,453	297,883	177,279	298,659	44,896	2,701,264
Hong Kong, China	652,172	866,911	1,648	811,984	228,301	201,772	27,402	2,790,192
Seoul, South Korea	652,160	866,911	361,748	351,871	175,730	304,389	40,498	2,753,306
Singapore, Singapore	652,171	866,911	-	1,021,156	175,894	222,162	23,840	2,962,134
London, UK	652,226	866,911	159,523	230,442	105,038	196,085	42,039	2,252,264
Los Angeles, US	652,170	866,911	8,587	307,659	92,984	162,526	35,498	2,126,335
New York, US	652,186	866,911	213,071	405,734	198,473	252,709	40,213	2,629,297

Figure 4: Annual Energy by End Use by City: Model with 50% WWR

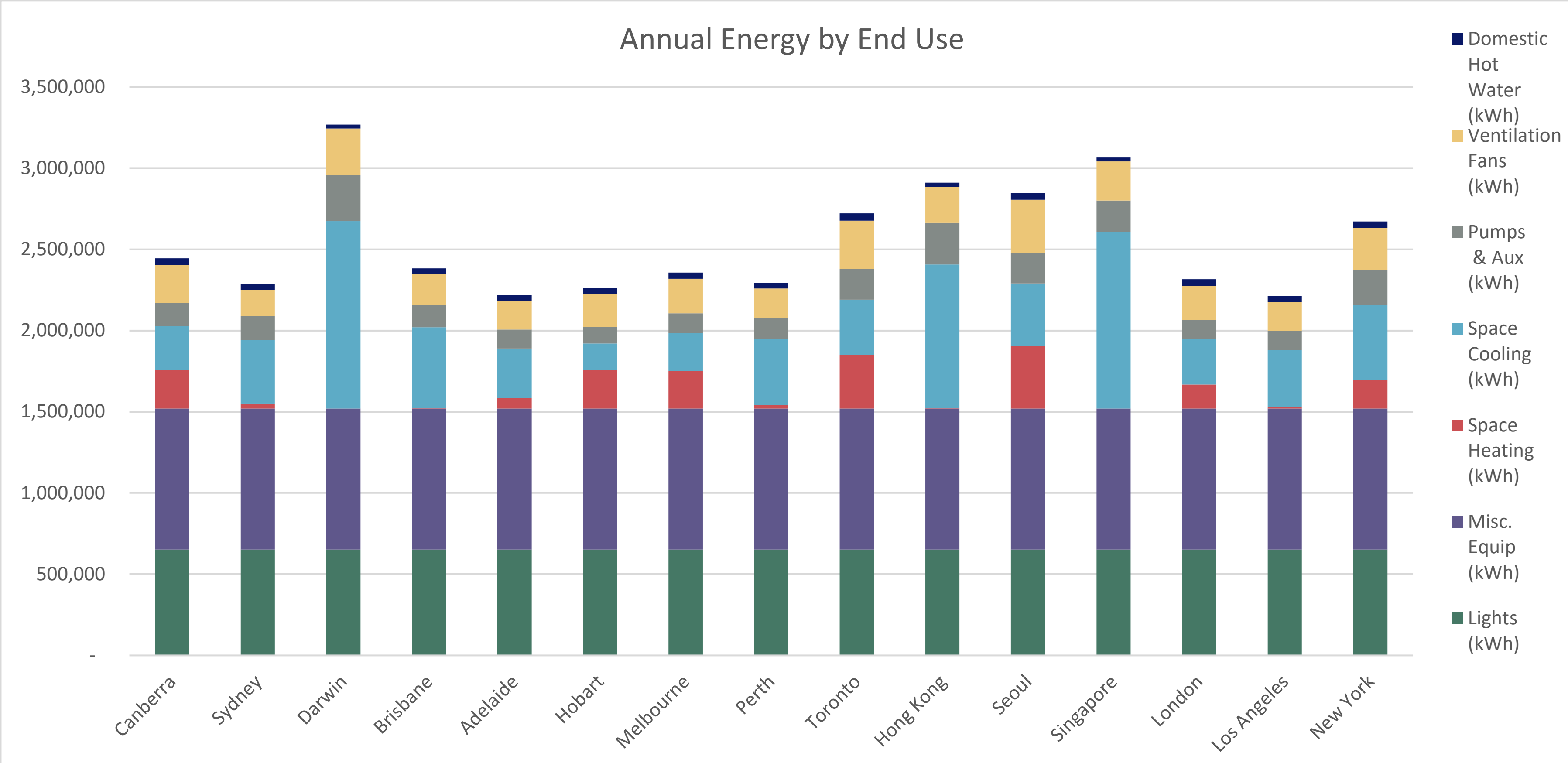


Table 9: Annual Energy By End Use by City: Model with 50% WWR

Location	Lights (kWh)	Misc. Equip (kWh)	Space Heating (kWh)	Space Cooling (kWh)	Pumps & Aux (kWh)	Ventilation Fans (kWh)	Domestic Hot Water (kWh)	Total (kWh)
Canberra, Australia	652,204	866,911	239,560	267,563	143,592	233,808	40,228	2,443,867
Sydney, Australia	652,199	866,911	32,117	390,163	147,168	162,597	34,270	2,285,425
Darwin, Australia	652,190	866,911	-	1,154,081	282,739	287,404	24,315	3,267,640
Brisbane, Australia	652,178	866,911	2,338	498,832	139,530	189,772	32,502	2,382,064
Adelaide, Australia	652,185	866,911	66,485	303,789	116,770	177,896	36,002	2,220,039
Hobart, Australia	652,214	866,911	237,316	163,577	102,085	200,461	40,563	2,263,128
Melbourne, Australia	652,210	866,911	231,536	232,379	123,100	212,233	38,710	2,357,079
Perth, Australia	652,201	866,911	21,178	406,357	127,912	184,228	34,183	2,292,969
Toronto, Canada	652,178	866,911	330,568	339,788	189,258	298,079	44,893	2,721,675
Hong Kong, China	652,171	866,911	2,115	885,320	256,930	218,762	27,401	2,909,612
Seoul, South Korea	652,157	866,911	387,465	383,597	186,870	328,647	40,497	2,846,145
Singapore, Singapore	652,170	866,911	-	1,088,547	193,147	239,955	23,840	3,064,570
London, UK	652,222	866,911	148,456	282,334	114,650	209,245	42,036	2,315,855
Los Angeles, US	652,170	866,911	11,081	351,371	115,323	180,276	35,497	2,212,630
New York, US	652,184	866,911	175,948	463,262	216,250	257,223	40,209	2,671,987

Figure 5: Annual Energy by End Use by City: Model with 60% WWR

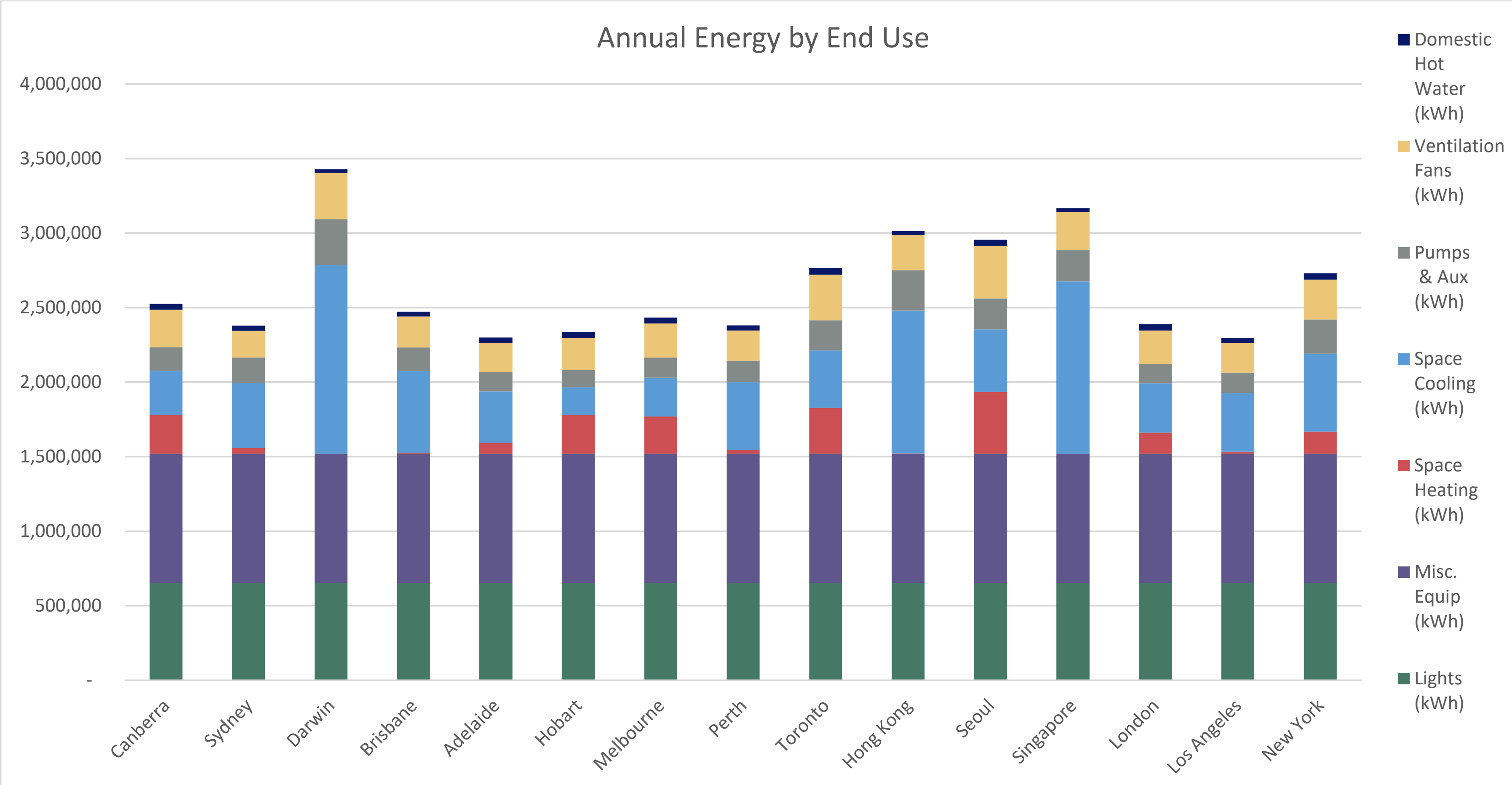


Table 10: Annual Energy By End Use by City: Model with 60% WWR

Location	Lights (kWh)	Misc. Equip (kWh)	Space Heating (kWh)	Space Cooling (kWh)	Pumps & Aux (kWh)	Ventilation Fans (kWh)	Domestic Hot Water (kWh)	Total (kWh)
Canberra, Australia	652,204	866,911	259,111	297,659	157,992	250,529	40,228	2,524,635
Sydney, Australia	652,199	866,911	38,753	437,883	170,348	178,566	34,269	2,378,929
Darwin, Australia	652,190	866,911	-	1,264,672	309,095	310,370	24,315	3,427,553
Brisbane, Australia	652,178	866,911	3,704	552,167	157,605	206,647	32,502	2,471,714
Adelaide, Australia	652,184	866,911	75,186	343,134	129,895	195,028	36,001	2,298,340
Hobart, Australia	652,213	866,911	260,034	186,199	114,485	217,222	40,563	2,337,627
Melbourne, Australia	652,209	866,911	249,550	261,216	135,958	227,896	38,710	2,432,450
Perth, Australia	652,200	866,911	26,846	453,192	143,548	202,733	34,183	2,379,613
Toronto, Canada	652,177	866,911	307,785	385,332	202,777	305,049	44,891	2,764,922
Hong Kong, China	652,170	866,911	2,737	958,634	269,095	235,556	27,401	3,012,504
Seoul, South Korea	652,156	866,911	415,303	419,095	206,959	354,001	40,497	2,954,922
Singapore, Singapore	652,170	866,911	-	1,156,198	209,828	256,835	23,840	3,165,782
London, UK	652,221	866,911	141,511	331,850	129,752	223,942	42,034	2,388,222
Los Angeles, US	652,170	866,911	13,499	393,639	138,242	197,619	35,496	2,297,576
New York, US	652,184	866,911	149,167	521,853	230,602	267,399	40,207	2,728,323

Figure 6: Annual Energy by End Use by City: Model with 70% WWR

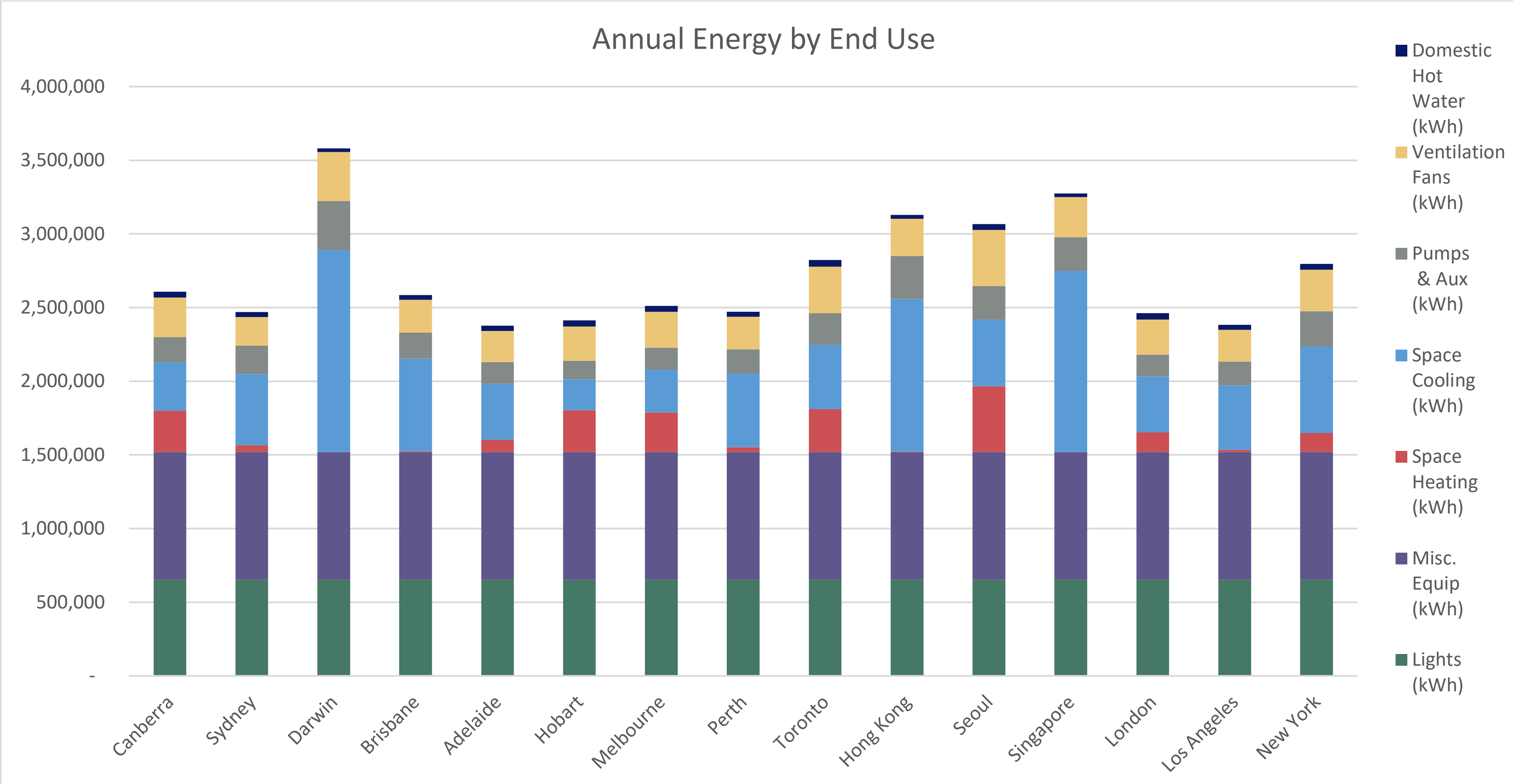


Table 11: Annual Energy By End Use by City: Model with 70% WWR

Location	Lights (kWh)	Misc. Equip (kWh)	Space Heating (kWh)	Space Cooling (kWh)	Pumps & Aux (kWh)	Ventilation Fans (kWh)	Domestic Hot Water (kWh)	Total (kWh)
Canberra, Australia	652,204	866,911	279,571	329,395	172,146	267,494	40,228	2,607,950
Sydney, Australia	652,199	866,911	46,386	483,610	192,845	194,442	34,269	2,470,663
Darwin, Australia	652,189	866,911	-	1,372,263	331,374	333,415	24,315	3,580,468
Brisbane, Australia	652,178	866,911	5,711	630,113	175,243	223,182	32,502	2,585,842
Adelaide, Australia	652,184	866,911	83,183	381,006	145,561	211,646	36,001	2,376,491
Hobart, Australia	652,213	866,911	283,730	209,491	126,357	233,264	40,562	2,412,529
Melbourne, Australia	652,209	866,911	268,652	291,203	149,252	244,201	38,709	2,511,136
Perth, Australia	652,200	866,911	33,546	500,120	163,720	221,185	34,182	2,471,863
Toronto, Canada	652,176	866,911	291,041	435,970	216,414	315,415	44,889	2,822,816
Hong Kong, China	652,170	866,911	3,405	1,035,383	292,433	252,003	27,401	3,129,706
Seoul, South Korea	652,156	866,911	445,661	454,526	225,887	381,189	40,497	3,066,828
Singapore, Singapore	652,170	866,911	-	1,230,264	227,712	272,876	23,839	3,273,774
London, UK	652,221	866,911	135,336	378,595	147,463	239,066	42,032	2,461,626
Los Angeles, US	652,170	866,911	16,612	436,287	161,509	214,751	35,496	2,383,737
New York, US	652,184	866,911	129,606	586,281	240,585	280,856	40,205	2,796,629

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Projected Energy Production – International

Solar Production

The table below summarizes the annual energy production of the BIPV by façade orientation for each of the locations analyzed. The production is expressed and annual kWh generated per kW of installed capacity. Values were based on the 50% glazing; 50% spandrel simulation runs.

Table 12: BIPV Annual Production by Facade

	South		West		East		North	
Location	Spandrel BIPV	Glazing BIPV	Spandrel BIPV	Glazing BIPV	Spandrel BIPV	Glazing BIPV	Spandrel BIPV	Glazing BIPV
	kWh/kW	kWh/kW	kWh/kW	kWh/kW	kWh/kW	kWh/kW	kWh/kW	kWh/kW
Canberra	481.3	482.2	1,133.8	1,137.2	693.4	690.2	1,088.8	1,097.3
Sydney	489.5	494.4	1,111.2	1,118.8	679.9	680.8	1,090.0	1,104.4
Darwin	559.0	568.8	883.7	893.6	1,280.3	1,296.6	1,008.8	1,017.1
Brisbane	554.6	564.0	1,155.4	1,167.0	742.3	747.6	1,057.3	1,074.5
Adelaide	451.8	453.5	837.5	838.3	1,066.3	1,072.3	1,045.4	1,053.2
Hobart	453.3	451.8	969.8	970.4	607.3	602.3	991.1	998.1
Melbourne	476.1	476.7	1,040.6	1,043.4	649.1	646.1	976.6	982.4
Perth	496.8	501.6	1,230.6	1,239.9	795.0	797.4	1,103.7	1,115.0
Toronto	933.2	929.3	727.2	719.2	704.3	695.7	345.2	339.1
Hong Kong	909.5	925.4	914.4	924.4	833.6	842.2	552.5	563.3
Seoul	1,076.8	1,086.8	588.0	582.4	975.0	973.4	428.0	427.9
Singapore	758.2	771.6	747.4	758.3	1,145.6	1,162.2	746.4	759.8
London	774.5	778.3	723.7	721.2	476.2	471.0	362.4	360.5
Los Angeles	1,240.9	1,253.8	1,264.7	1,272.7	774.6	774.7	459.4	461.4
New York	1,033.1	1,038.5	917.5	914.6	614.6	608.0	407.3	406.1

Figure 7 to Figure 10 and Table 13 to Table 16 show the annual electrical generation across all 15 cities for each BIPV type and all 4 values for WWR. The roof mounted PV array was set at a 10° tilt recognizing tilt limitations of ballasted racking systems.

Figure 7: Annual PV Generation by City and BIPV Type in 40% WWR

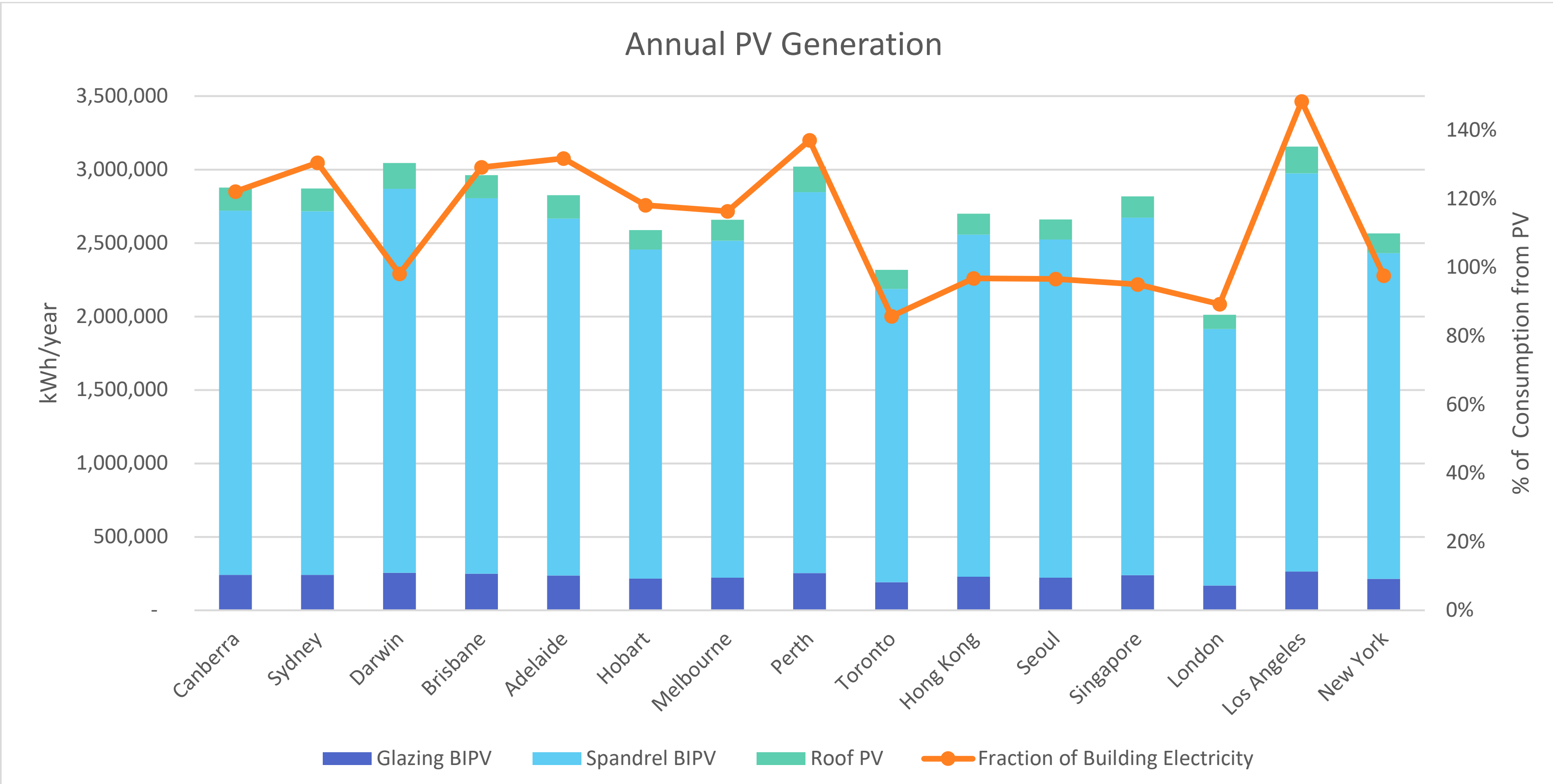

Table 13: Annual PV Generation by City and BIPV Type in 40% WWR

Location	Glazing BIPV Annual kWh	Spandrel BIPV Annual kWh	Roof PV Annual kWh	Total PV Generation kWh	Annual Building Consumption kWh	Fraction of Annual use by PV
Canberra, Australia	240,432	2,479,645	156,131	2,876,208	2,354,317	122%
Sydney, Australia	241,410	2,475,526	153,747	2,870,683	2,198,530	131%
Darwin, Australia	255,339	2,613,207	176,497	3,045,043	3,103,859	98%
Brisbane, Australia	250,152	2,554,402	156,427	2,960,981	2,291,223	129%
Adelaide, Australia	235,925	2,429,949	160,272	2,826,146	2,144,190	132%
Hobart, Australia	216,603	2,239,261	131,183	2,587,047	2,189,834	118%
Melbourne, Australia	222,169	2,293,958	142,801	2,658,928	2,285,135	116%
Perth, Australia	252,622	2,593,422	174,094	3,020,138	2,202,844	137%
Toronto, Canada	191,033	1,996,372	129,075	2,316,480	2,701,264	86%
Hong Kong, China	228,350	2,327,696	144,476	2,700,522	2,790,192	97%
Seoul, South Korea	222,867	2,300,658	137,061	2,660,586	2,753,306	97%
Singapore, Singapore	238,942	2,433,567	143,976	2,816,485	2,962,134	95%
London, UK	168,460	1,746,105	97,119	2,011,684	2,252,264	89%
Los Angeles, US	263,553	2,709,769	183,025	3,156,347	2,126,335	148%
New York, US	214,082	2,216,718	134,488	2,565,288	2,629,297	98%

Figure 8: Annual PV Generation by City and BIPV Type in 50% WWR

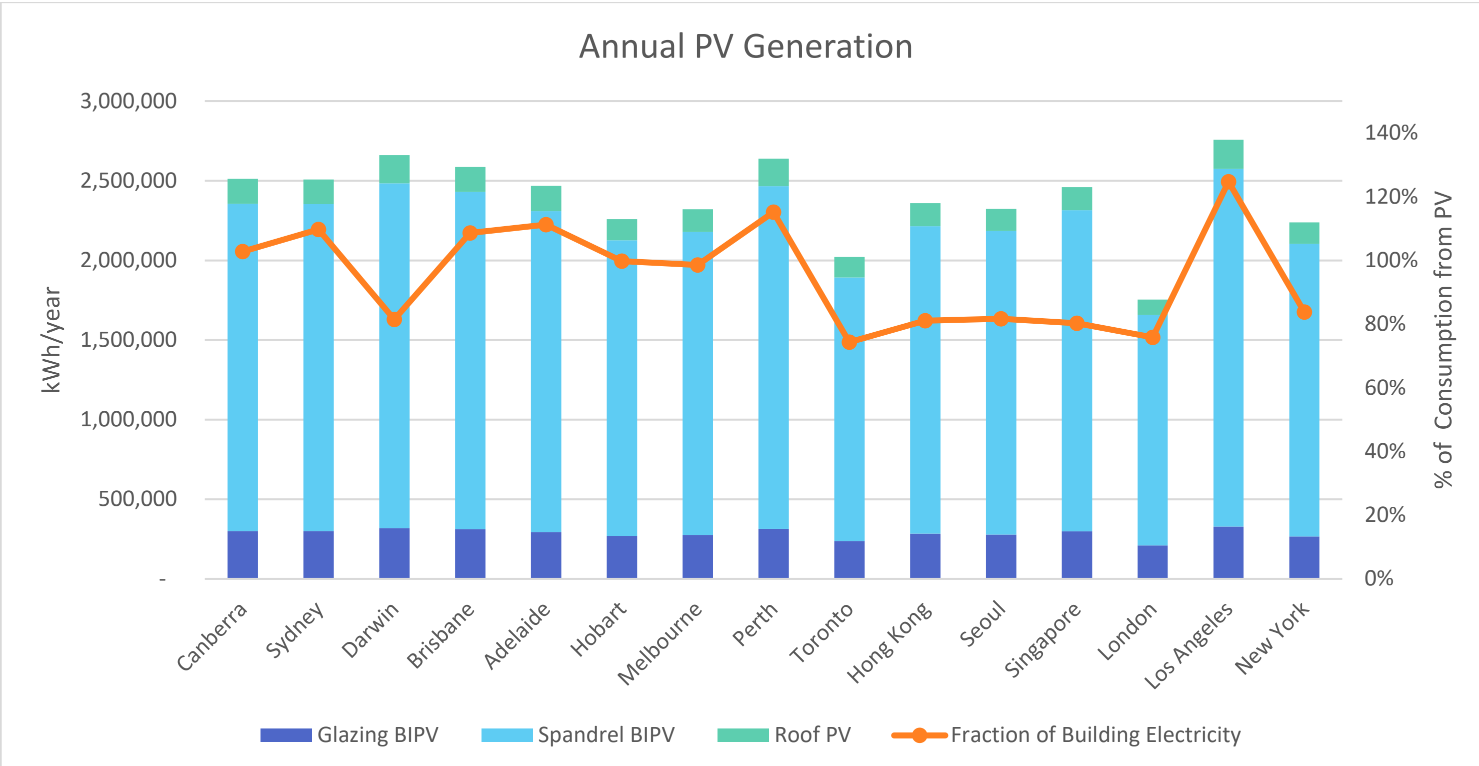

Table 14: Annual PV Generation by City and BIPV Type in 50% WWR

Location	Glazing BIPV Annual kWh	Spandrel BIPV Annual kWh	Roof PV Annual kWh	Total PV Generation kWh	Annual Building Consumption kWh	Fraction of Annual use by PV
Canberra, Australia	299,333	2,056,069	156,131	2,511,533	2,443,867	103%
Sydney, Australia	300,559	2,052,622	153,747	2,506,928	2,285,425	110%
Darwin, Australia	317,786	2,166,693	176,497	2,660,976	3,267,640	81%
Brisbane, Australia	311,425	2,118,059	156,427	2,585,911	2,382,064	109%
Adelaide, Australia	293,666	2,014,653	160,272	2,468,591	2,220,039	111%
Hobart, Australia	269,690	1,856,682	131,183	2,257,555	2,263,128	100%
Melbourne, Australia	276,585	1,902,031	142,801	2,321,417	2,357,079	98%
Perth, Australia	314,458	2,150,382	174,094	2,638,934	2,292,969	115%
Toronto, Canada	237,829	1,655,222	129,075	2,022,126	2,721,675	74%
Hong Kong, China	284,280	1,930,044	144,476	2,358,800	2,909,612	81%
Seoul, South Korea	277,512	1,907,575	137,061	2,322,148	2,846,145	82%
Singapore, Singapore	297,440	2,017,858	143,976	2,459,274	3,064,570	80%
London, UK	209,740	1,447,619	97,119	1,754,478	2,315,855	76%
Los Angeles, US	328,106	2,246,868	183,025	2,757,999	2,212,630	125%
New York, US	266,553	1,837,980	134,488	2,239,021	2,671,987	84%

Figure 9: Annual PV Generation by City and BIPV Type in 60% WWR

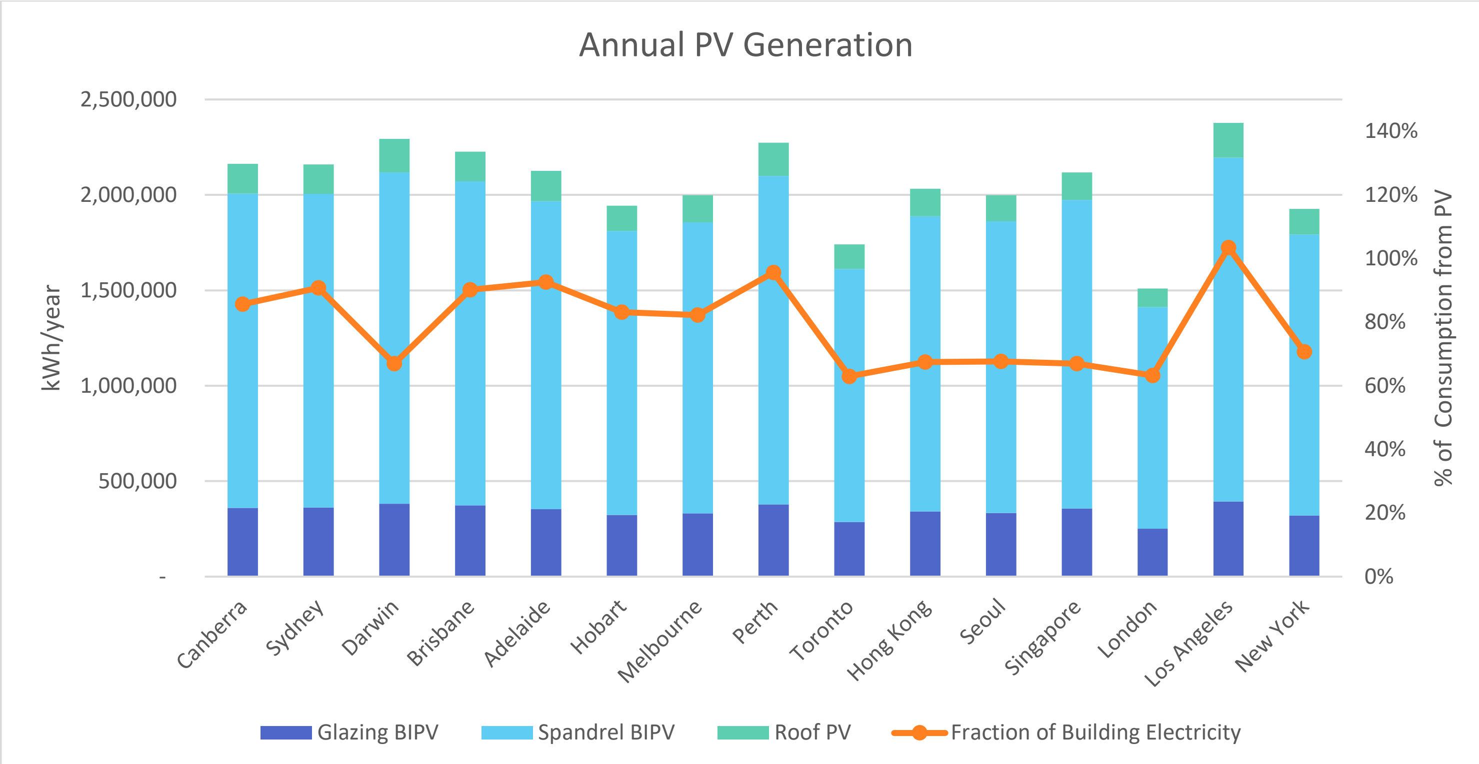

Table 15: Annual PV Generation by City and BIPV Type in 60% WWR

Location	Glazing BIPV Annual kWh	Spandrel BIPV Annual kWh	Roof PV Annual kWh	Total PV Generation kWh	Annual Building Consumption kWh	Fraction of Annual use by PV
Canberra, Australia	359,486	1,647,315	156,131	2,162,932	2,524,635	86%
Sydney, Australia	360,946	1,644,662	153,747	2,159,355	2,378,929	91%
Darwin, Australia	381,721	1,735,335	176,497	2,293,553	3,427,553	67%
Brisbane, Australia	373,994	1,696,903	156,427	2,227,324	2,471,714	90%
Adelaide, Australia	352,712	1,613,947	160,272	2,126,931	2,298,340	93%
Hobart, Australia	323,863	1,487,758	131,183	1,942,804	2,337,627	83%
Melbourne, Australia	332,168	1,523,825	142,801	1,998,794	2,432,450	82%
Perth, Australia	377,673	1,722,502	174,094	2,274,269	2,379,613	96%
Toronto, Canada	285,608	1,326,113	129,075	1,740,796	2,764,922	63%
Hong Kong, China	341,408	1,546,207	144,476	2,032,091	3,012,504	67%
Seoul, South Korea	333,238	1,528,634	137,061	1,998,933	2,954,922	68%
Singapore, Singapore	357,244	1,616,307	143,976	2,117,527	3,165,782	67%
London, UK	251,857	1,160,095	97,119	1,509,071	2,388,222	63%
Los Angeles, US	394,051	1,800,118	183,025	2,377,194	2,297,576	103%
New York, US	320,080	1,472,824	134,488	1,927,392	2,728,323	71%

Figure 10: Annual PV Generation by City and BIPV Type in 70% WWR

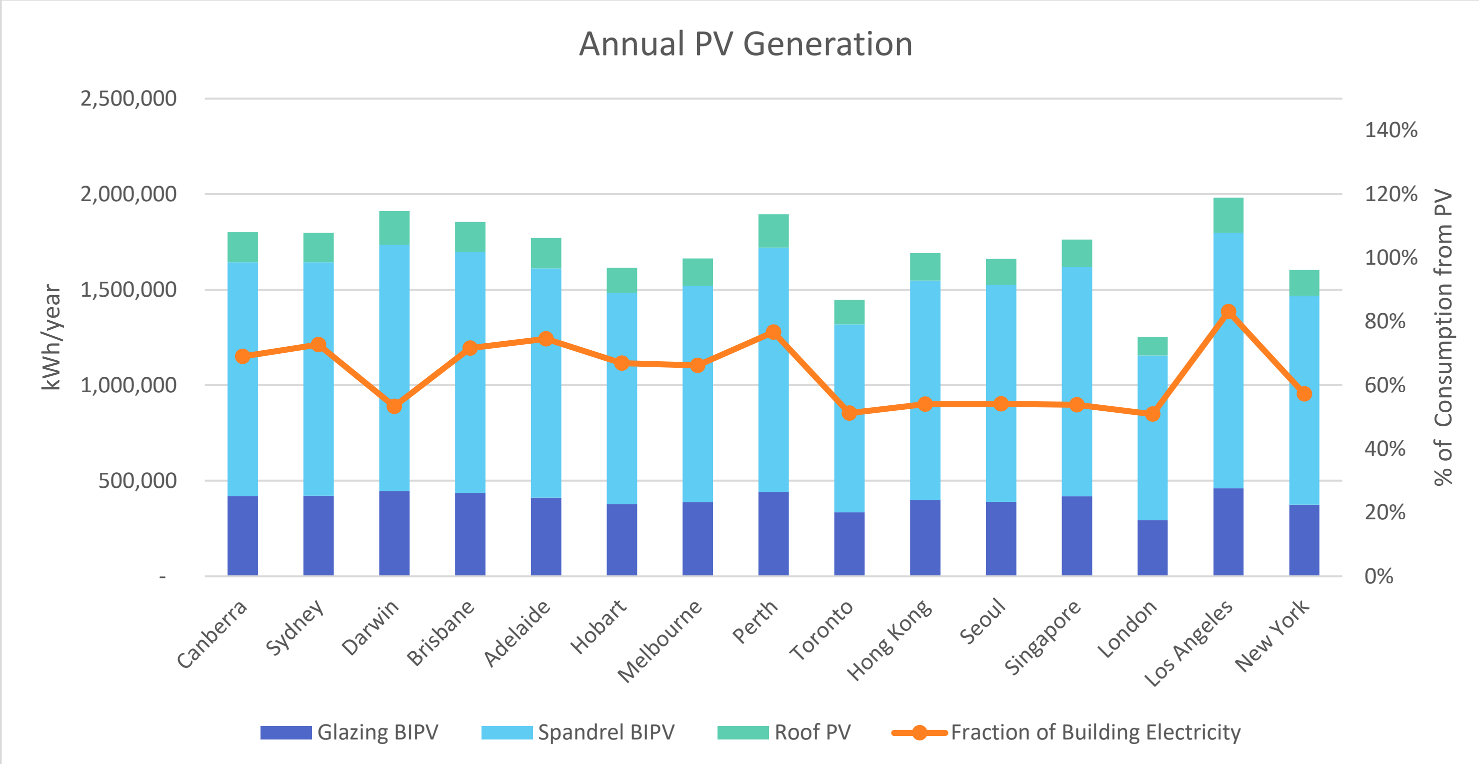

Table 16: Annual PV Generation by City and BIPV Type in 70% WWR

Location	Glazing BIPV Annual kWh	Spandrel BIPV Annual kWh	Roof PV Annual kWh	Total PV Generation kWh	Annual Building Consumption kWh	Fraction of Annual use by PV
Canberra, Australia	420,713	1,223,611	156,131	1,800,455	2,607,950	69%
Sydney, Australia	422,429	1,221,628	153,747	1,797,804	2,470,663	73%
Darwin, Australia	446,742	1,288,800	176,497	1,912,039	3,580,468	53%
Brisbane, Australia	437,711	1,260,363	156,427	1,854,501	2,585,842	72%
Adelaide, Australia	412,799	1,198,702	160,272	1,771,773	2,376,491	75%
Hobart, Australia	379,033	1,104,941	131,183	1,615,157	2,412,529	67%
Melbourne, Australia	388,754	1,131,653	142,801	1,663,208	2,511,136	66%
Perth, Australia	442,021	1,279,275	174,094	1,895,390	2,471,863	77%
Toronto, Canada	334,285	984,505	129,075	1,447,865	2,822,816	51%
Hong Kong, China	399,565	1,148,377	144,476	1,692,418	3,129,706	54%
Seoul, South Korea	390,009	1,135,147	137,061	1,662,217	3,066,828	54%
Singapore, Singapore	418,083	1,200,305	143,976	1,762,364	3,273,774	54%
London, UK	294,792	861,411	97,119	1,253,322	2,461,626	51%
Los Angeles, US	461,162	1,337,184	183,025	1,981,371	2,383,737	83%
New York, US	374,631	1,093,797	134,488	1,602,916	2,796,629	57%

Greenhouse Gas Emissions

The Archetype 40-storey design was envisioned with no on-site sources of combustion. All building systems use electricity as their source. The scope 1 greenhouse gas emissions, emissions from assets owned and operated by the property, would be limited to refrigerant leakage and are not included in this study. The scope 2 emissions are emissions off-site used directly produce energy used on site. The GHG emissions resulting from the production of electricity vary considerably by jurisdiction depending on the sources of electrical generation. Representative emissions factors for electricity production for each of the locations evaluated in this study have been shown in Table 17.

Figure 11: GHG Emissions for Building and Offset by PV by Location - 40% WWR

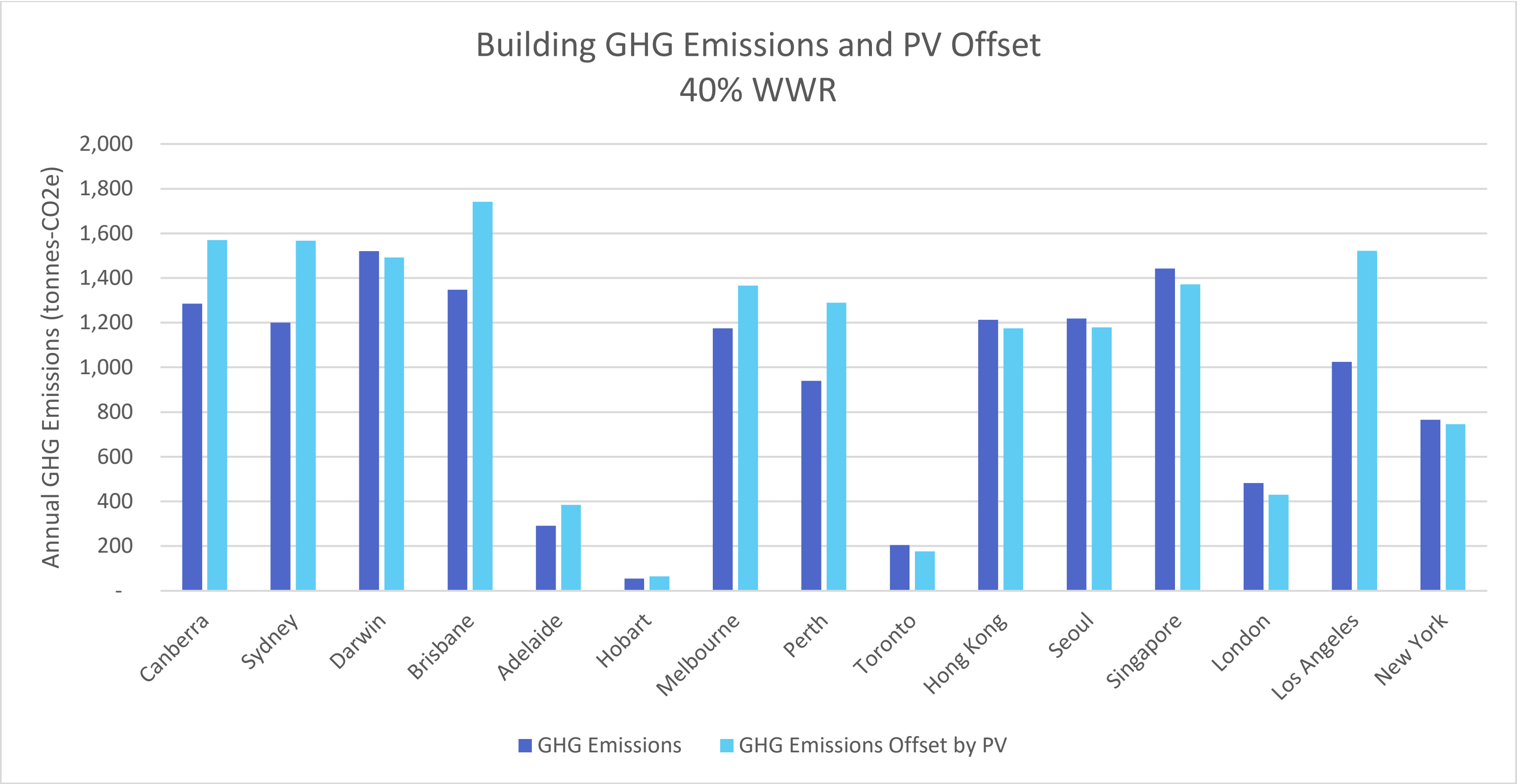

Table 17: GHG Emissions - 40% WWR

		40% WWR	
Location	Electricity Emissions Factor	Building GHG emissions	Emissions offset by PV
	$g\text{-}CO_{2e}/kWh$	$tonnes\text{-}CO_{2e}$	$tonnes\text{-}CO_{2e}$
Canberra, Australia	546	1,285	1,570
Sydney, Australia	546	1,200	1,567
Darwin, Australia	490	1,521	1,492
Brisbane, Australia	588	1,347	1,741
Adelaide, Australia	136	292	384
Hobart, Australia	25	55	65
Melbourne, Australia	514	1,174	1,367
Perth, Australia	427	940	1,290
Toronto, Canada	76	205	176
Hong Kong, China	435	1,213	1,175
Seoul, South Korea	443	1,219	1,179
Singapore, Singapore	487	1,442	1,372
London, UK	214	482	431
Los Angeles, US	482	1,025	1,521
New York, US	291	765	746

– Emissions Factor source: (Electricity Maps ApS, 2024)

The figure below shows the high window-to-wall ratio case. In this case, building energy use, driven primarily by cooling loads, have gone up whereas the production of the photovoltaic systems has gone down due to the higher ratio of glazing BIPV to spandrel BIPV.

Figure 12: GHG Emissions for Building and Offset by PV by Location - 70% WWR

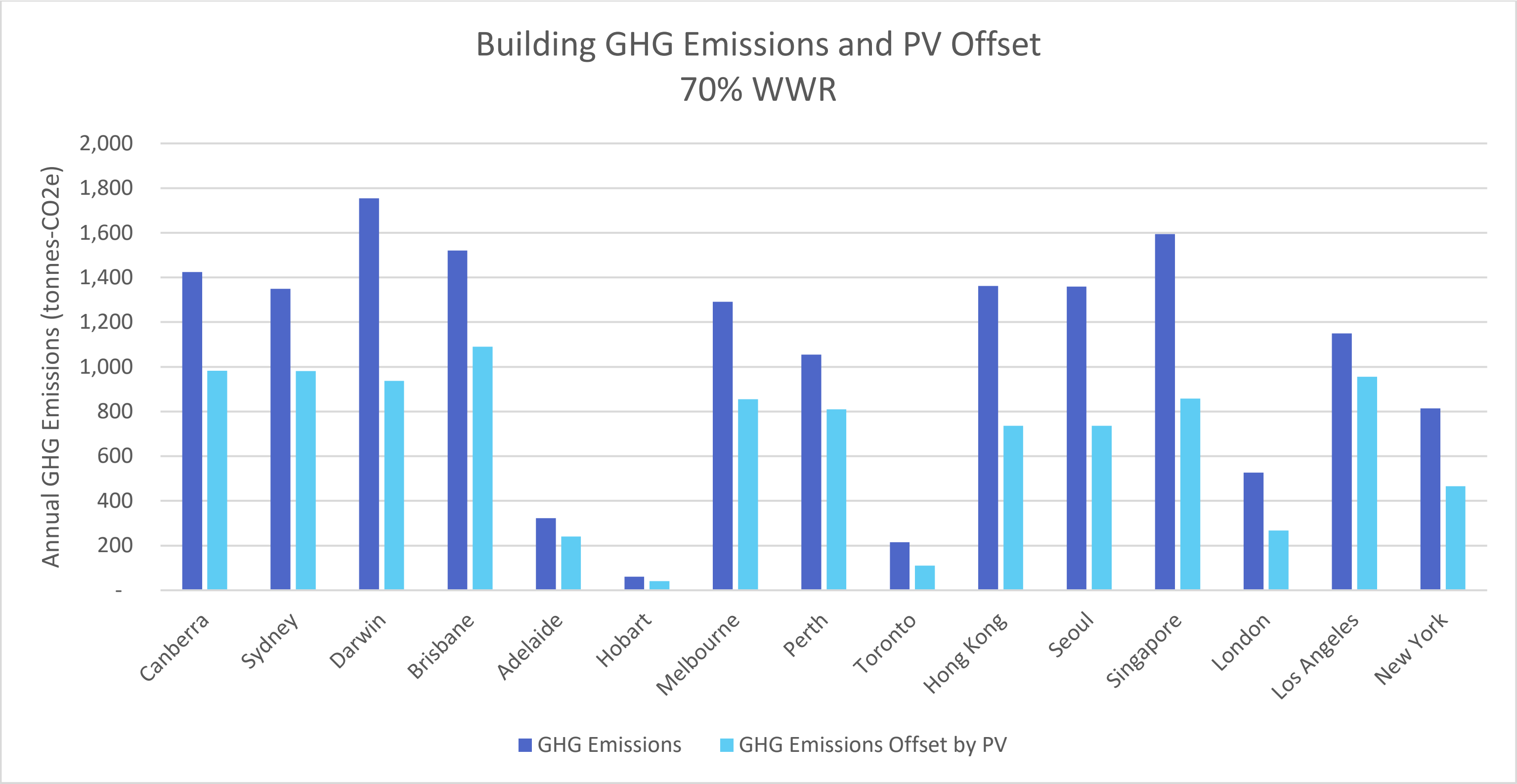

Table 18: GHG Emissions - 70% WWR

		70% WWR	
Location	Electricity Emissions Factor	Building GHG emissions	Emissions offset by PV
	g-CO_{2e}/kWh	tonnes-CO_{2e}	tonnes-CO_{2e}
Canberra, Australia	546	1,424	983
Sydney, Australia	546	1,349	982
Darwin, Australia	490	1,754	937
Brisbane, Australia	588	1,520	1,090
Adelaide, Australia	136	323	241
Hobart, Australia	25	60	40
Melbourne, Australia	514	1,291	855
Perth, Australia	427	1,055	809
Toronto, Canada	76	215	110
Hong Kong, China	435	1,361	736
Seoul, South Korea	443	1,359	736
Singapore, Singapore	487	1,594	858
London, UK	214	527	268
Los Angeles, US	482	1,149	955
New York, US	291	814	466

Conclusions & Key Takeaways

This report identifies the renewable output from the high-rise office building archetype with ClearVue on glazing and dark spandrel panels among 15 international cities.

It shows that BIPV helps considerably reduce both energy use intensity and greenhouse gas emissions in seeking to meet the Toronto Green Standard absolute intensity target values.

For the model with 40% WWR, buildings in 11 cities are able to achieve Net Zero or Net Positive Energy with the building mounted PV arrays. All sites had over 85% of their annual consumption generated by the building mounted photovoltaic systems.

As the window-to-wall ratio of the buildings was increased, the area of the higher W/m² BIPV spandrel panel was offset by glazing reducing the overall building renewable generation while the building cooling load increased. However, even at 70% window-to-wall ratio, all locations of the Archetype 40-storey model had more than 50% of their annual energy generated by the building mounted PV arrays.

The emissions savings by the PV systems varied with the jurisdiction emissions factor as well as with the location solar resource but ranged up to over 1,500 to 1,600 tonnes of CO_{2e} (43 kg-CO_{2e}/m² of gross floor area) in regions with high solar availability and higher emissions factors.

Limitations

Building energy simulation is a comparative analysis of building design efficiency measures and does not aim to predict future energy bills or absolute energy consumption.

Energy modelling is intended to analyse design-based energy loads and less accurately evaluates occupant dependent building loads. Energy modelling includes assumptions for building occupancy and occupant behavior, operational and maintenance practices, schedules, air leakage and plug load which can substantially impact energy consumption.

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