THE CARBON SWEET SPOT

DESIGN TRADEOFFS FOR EMBODIED AND OPERATIONAL CARBON IN NEW BUILDINGS

ULI

ABOUT

Urban Land Institute

Urban Land Institute is a global, member-driven organization comprising more than 48,000 real estate and urban development professionals dedicated to advancing the Institute's mission of shaping the future of the built environment for transformative impact in communities worldwide. ULI's interdisciplinary membership represents all aspects of the industry, including developers, property owners, investors, architects, urban planners, public officials, real estate brokers, appraisers, attorneys, engineers, financiers, and academics. Established in 1936, the Institute has a presence in the Americas, Europe, and Asia Pacific regions, with members in 84 countries.

Randall Lewis Center

The ULI Randall Lewis Center for Sustainability in Real Estate leads the real estate industry in creating places and buildings where people and the environment thrive. In collaboration with ULI members and partners, the Lewis Center drives industry transformation, cultivates leaders and champions, and helps foster solutions for sustainable, resilient, healthy, and equitable cities and communities. The center pursues these goals via cutting-edge research, global convenings, community technical assistance, and other strategies. The center's main programs are Decarbonization, Urban Resilience, and Healthy Places.

Discover transformative practices for real estate and land use at uli.org/sustainability. Connect with the Lewis Center at sustainability@uli.org.

KPF

Kohn Pedersen Fox (KPF) is a unified architectural practice focused on the design of buildings of all types and scales, in all geographic regions. KPF's projects include the world's tallest towers, longest spans, most varied programs, and inventive forms. The goal that binds the firm's work—and what motivates its efforts—is finding the smartest solution for each project. KPF believes that the best design is the product of an open-minded search, one without preconceptions or stylistic formulae.

University of Washington's Integrated Design Lab

The University of Washington's Center for Integrated Design (UW CID) is a research center operated by the Department of Architecture in the College of Built Environments at the university. Its research organization, the Integrated Design Lab (IDL), is a self-sustaining lab that includes interdisciplinary faculty, staff, students, professional collaborators, and partner organizations.

Our mission is to discover solutions that overcome the most difficult building performance barriers and to meet the building industry's goals of moving toward radically higher performing buildings and healthy urban environments. We advance our mission through interconnected research, technical assistance, and education and outreach.

This Report

With increasing emphasis on decarbonization, building owners and developers face myriad choices as they try to balance cost and value and meet social and corporate-level carbon emissions reduction goals. This report presents three hypothetical life-cycle carbon analyses of buildings in different geographic and regulatory contexts: London, New York, and Singapore. These examples illustrate how real estate decision-makers can navigate the tradeoffs and opportunities that arise when pursuing reductions in both embodied and operational carbon emissions (life-cycle emissions). Based on the results of these example analyses and discussions with leading developers and industry experts, this report highlights the critical design decisions that impact the building facade and offers frameworks for considering total carbon emissions over the life of a building investment. Ultimately, it identifies the whole life-cycle carbon "sweet spots" for new building design.

Cover photo: One Crown Place, London, a mixed-use development by KPF. (Hufton + Crow, courtesy KPF)

2001 L Street, NW | Suite 200 | Washington, DC 20036-4948

Recommended bibliographic listing: Urban Land Institute. *The Carbon Sweet Spot: Design Tradeoffs for Embodied and Operational Carbon in New Buildings*. Washington, DC: Urban Land Institute, 2024.

CONTENTS

EXECUTIVE SUMMARY

With increasing emphasis on decarbonization, building owners and developers face myriad choices as they try to balance cost and value and meet social and corporate-level carbon emissions reduction goals. Emissions in the building sector primarily fall into categories of “operational” and “embodied” carbon emissions; combined, they account for nearly 40 percent of global carbon dioxide released into the atmosphere.

This report presents three hypothetical analyses of buildings in different geographic and regulatory contexts: London, New York, and Singapore. These examples illustrate how real estate decision-makers can navigate the tradeoffs and opportunities that arise when pursuing reductions in both embodied and operational carbon emissions (known together as life-cycle emissions).

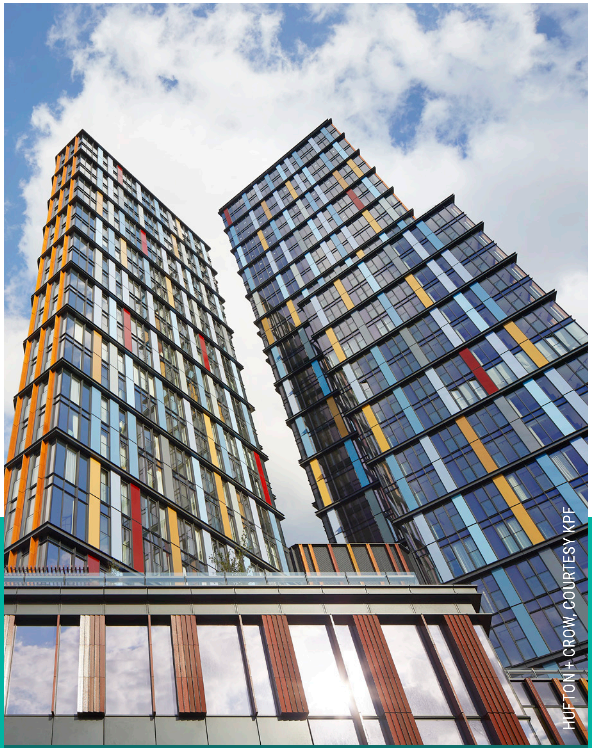
The tradeoffs are particularly pronounced in decisions related to the building envelope. Building enclosure components are long-lasting—with a service life typically exceeding 25 years—and among the costliest of all building systems. They also have an outsized impact on operational carbon emissions and energy consumption over the life of a building, both regulating heating and cooling loads and enabling the advanced mechanical systems required for efficiency and electrification.

Based on the results of the three project analyses and discussions with leading developers and industry experts, this report highlights the critical design decisions that impact the building facade and offers frameworks for considering total carbon emissions over the life of a building investment. Ultimately, it suggests a process by which decision-makers can identify the whole life-cycle carbon “sweet spots” for their buildings.

Three Buildings, Three Contexts

The three buildings examined for this report offer a glimpse into a variety of architectural design decisions, climate contexts, grid carbon intensities, and use types.

- **One Crown Place** in Hackney, London, was chosen to explore the effects of glass area and wall insulation on a residential building in a mild climate where electricity for heating and cooling is already low in carbon emissions.
- The **One Vanderbilt** office tower in New York City provided an opportunity to examine the effect of aluminum frame area and double or triple glazing in a climate with moderately cold winters and hot summers with a high-carbon-intensity electrical grid that is slated to rapidly decarbonize.
- The **18 Robinson** building is mixed-use high-rise, situated in the hot equatorial climate of Singapore. It served as the basis for investigating the life-cycle carbon impact of fixed shading elements in a cooling-dominated climate where building materials are typically sourced from significant distances.


HUFTON + CROW, COURTESY KPF

ONE CROWN PLACE, LONDON


RAIMUND KOCH, COURTESY KPF

ONE VANDERBILT, NEW YORK CITY


TIM GRIFFITH, COURTESY KPF

18 ROBINSON, SINGAPORE

Key Takeaways

The analysis determined that as developers consider carbon impacts for their buildings over a given lifespan of 30 years, strategies often highlighted for carbon reduction (such as triple-pane windows or external shades) must be carefully designed to optimize total life-cycle carbon. In particular, the following lessons gleaned from the specific buildings analyzed offer examples of ways to find the carbon “sweet spot”:

- **Carbon analyses can consider both operational and embodied carbon for maximum impact.** Understanding operational and embodied carbon tradeoffs can improve building performance and deliver the best value-to-cost ratio.
- **The amount of glazing on a building’s facade significantly influences both embodied and operational carbon emissions.** Strategically planning the placement of glazing areas to minimize their extent and optimize design for low carbon emissions is crucial.
- **Triple glazing should be carefully assessed.** It may contribute to more embodied emissions than it saves in operational emissions.
- **Increasing wall insulation tends to make only a modest difference on total carbon emissions when starting with standard code minimums.** Increasing wall insulation tends to reduce the need for mechanical heating, thus lowering operational emissions. Embodied emissions, however, increase with more insulation to the point of negating the savings in operational emissions, depending on the insulation type and sourcing.
- **Smaller curtain wall module widths can increase total carbon emissions.** Aluminum frames that make up standard curtain wall systems are carbon intensive. Smaller curtain wall modules tend to have more curtain wall framing material, significantly increasing embodied carbon. Operational carbon also increases with smaller wall modules, due to thermal bridging and air infiltration. Larger modules can reduce these impacts.
- **Shading devices may increase total carbon emissions but significantly reduce peak loads.** When using exterior shading, it can be strategically designed to optimize reduction in operational emissions while using less material.
- **Understanding the impact of local fuel sources and decarbonization policy is key to navigating carbon tradeoffs.** Local trajectories for grid cleanliness and building performance rules can significantly influence operational carbon emissions over a building’s service life and affect how much a developer may want to invest in added materials and some increases in embodied carbon to achieve operational savings.
- **Reducing the carbon impact of materials by designing for longevity, choosing recyclable materials, and considering building reuse can optimize a material’s impact on reducing operational carbon.** A building that is flexible to future uses and built to last will make the most of the embodied carbon spent to built it by increasing life-cycle value.

INTRODUCTION

As decarbonization increasingly becomes a global imperative for the real estate industry, building owners and developers are seeking to reduce carbon emissions associated with construction and operations. Accelerating climate risks, investor expectations, tenant preferences, and new regulations are all driving real estate decision-makers toward significant investment in low-carbon options.

Emissions in the building sector primarily fall into categories of “embodied” and “operational” carbon emissions. Combined, the two account for nearly 40 percent of global CO_2 released into the atmosphere. *Embodied emissions* are the carbon associated with construction, maintenance, and deconstruction activities throughout the life cycle of a building. Examples include sourcing raw materials, component manufacturing, transport and installation, renovations and fit-outs, and eventual demolition and reuse. *Operational emissions* stem from the ongoing energy needed for heating, cooling, lighting, ventilation, and tenant electricity consumption over a building’s life cycle.

Finding ways to reduce both the embodied and operational carbon of a building is a key priority for developers across the globe. According to Michael Long, director of sustainability at New World Development Company Limited, Hong Kong,

"Low-carbon measures that also tie with efficiency/resource conservation and reduce operational costs remain the greatest priority and most logical place to start for any organization."

Decisions to invest in sustainable building performance often pose tradeoffs between embodied and operational carbon emissions—in short, they require designs that hit the carbon "sweet spot." Figure 1 shows the impact of 12 different envelope designs on life-cycle carbon over a 30-year period. The different designs represent various levels of focus on reducing embodied versus operational carbon, resulting in different quantities of total building life-cycle carbon and thus hitting or missing the sweet spot.[1]

Developers and their design teams can arrive at suboptimal designs in two ways, by underinvesting or by overinvesting in energy efficiency–related design strategies. As shown in figure 1, underinvestment occurs when designs use insufficient energy-reducing design measures (and embodied carbon) and fail to contain operational carbon emissions (design 1). Overinvestment occurs when building designs add excessive material and embodied carbon with the intention of reducing operational carbon, but that extra material is not justified by significant operational reductions, or "returns" (design 12). In the ideal design (design 6), the **total carbon**—not just the embodied or operational carbon—is minimized for a given time frame (e.g., by 2030), by using just enough additional building material to significantly reduce operational emissions.

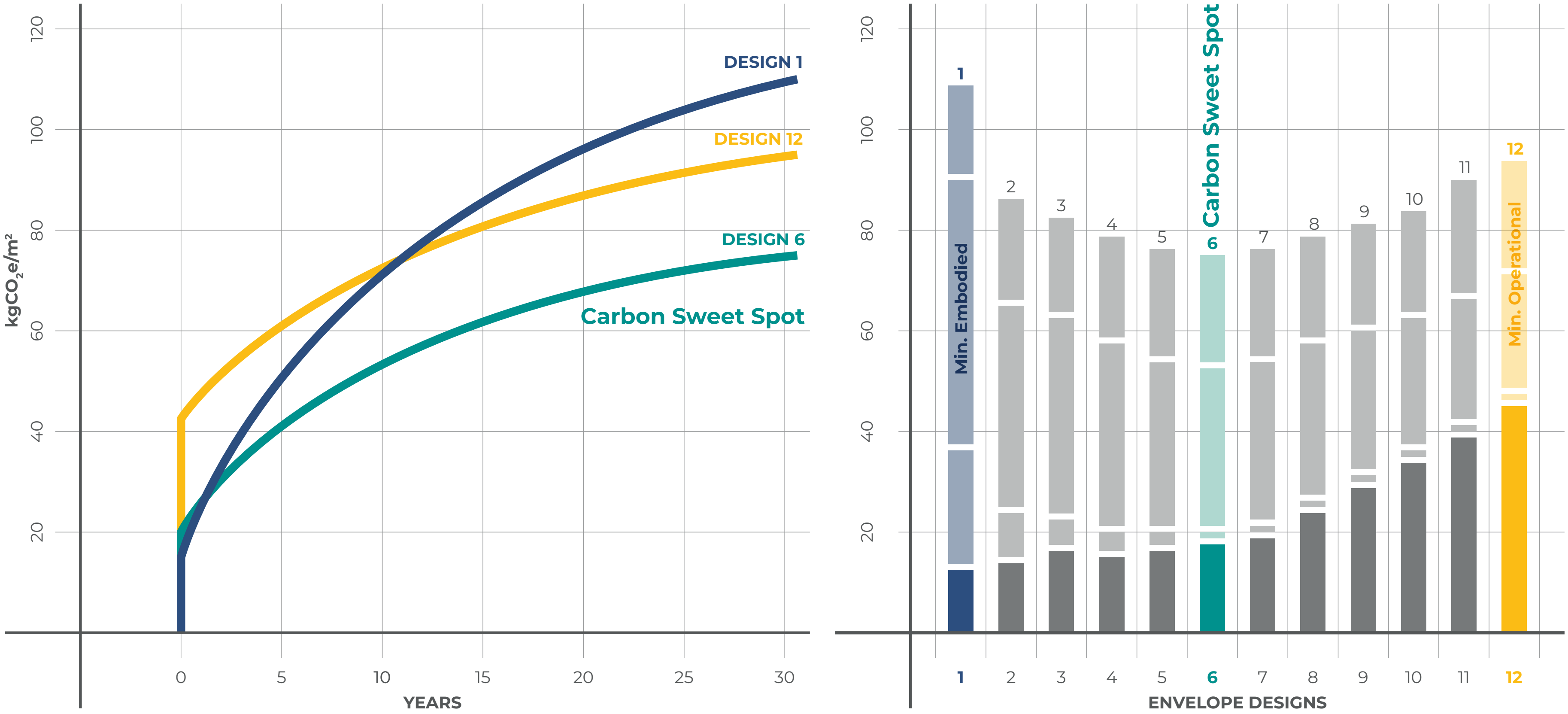


FIGURE 1. Cumulative 30-year emissions for 12 different building designs, reflecting various levels of focus on reducing embodied or operational carbon. Design 1 minimizes attention to embodied carbon, and the result is high operational carbon emissions; design 12 focuses much more on embodied carbon and achieves minimal operational carbon, but life-cycle carbon remains high; design 6 focuses just enough on embodied carbon to achieve significant operational carbon reductions, resulting in the lowest life-cycle carbon—the sweet spot.

The design of the building envelope can thus be understood as a multicriteria decision-making process. Developers and designers concerned with CO_2 emissions can consider a total carbon, life-cycle approach that balances upfront embodied carbon "investments" against operational carbon "returns," through a whole building life-cycle assessment.

The carbon sweet spot for buildings is not universal. Regional energy policy, local demands for heating and cooling, manufacturing limitations, and building design needs call for different approaches to decision-making in different global markets. This report presents hypothetical analyses of three real-world projects, exploring key tradeoffs between embodied and operational carbon in facade design for commercial real estate developments across the globe. It outlines key drivers and interrelationships of carbon emissions:

- Carbon intensity of the energy grid
- Thermal performance of the facade
- Material quantities and assemblies
- Material specifications and sourcing
- Projected rates of electricity decarbonization
- Impact of climate and regulation

The project analyses are drawn from three exemplary high-rise developments in North America, the United Kingdom, and Asia Pacific, all designed by Kohn Pedersen Fox (KPF). Each analysis uses the actual built project as a baseline to test the impact of hypothetical alternative design decisions, such as different window-to-wall ratios (WWR), on embodied and operational (or life-cycle) carbon emissions for 2030 and beyond. The alternatives were developed to explore key tradeoffs and sweet spots in facade design. The explorations presented are not intended as a prescriptive formula for any given building, but rather as a window into key variables a carbon-conscious building owner and design team can consider when weighing building investment decisions.

The projects were chosen because of key differences in their cities' development context, carbon policy environment, and physical climate. Figure 2 summarizes these variations; they are explored in more detail in the Case Studies section.

	LONDON	NEW YORK	SINGAPORE
CARBON CONTEXT	Clean grid; ambitious decarbonization goals and requirements for high-performing buildings	Slightly cleaner grid than U.S. average, with state plan to decarbonize by 2040; strict building performance legislation in place	Somewhat more carbon-intense grid, but on the lower end globally and getting cleaner; national tax on carbon emissions and net zero goals
CLIMATE CONTEXT	Temperate, mild, and consistent year-round	Cold winters and warm summers	Tropical, with year-round warm temperatures and high humidity
TAKEAWAYS	In this context, WWR has largest impact on carbon and window area can be minimized as practical; triple glazing significantly increases carbon because embodied emissions rise significantly while operational emissions do not decrease substantially; increasing wall insulation from RSI 3.5 to RSI 5.3 (R-20 to R-30) provides only modest carbon reductions for the same reason.	In this context, increasing the spacing of mullions and using larger glass panels can significantly reduce carbon; triple glazing should be carefully assessed as embodied carbon increases may exceed operational carbon savings; less glass area (WWR of 50% versus 65%) and increased insulation of spandrel panels provide only minimal life-cycle carbon reductions.	In this context, shade devices of all depths and materials increase embodied carbon more than they save in operational carbon; however, they reduce peak loads significantly, which allows for smaller and more efficient mechanical cooling systems and has a knock-on effect in terms of both embodied and operational carbon.

FIGURE 2. How variations by project location (carbon emissions of the utility grid, local policy, and geographical climate zone) affect carbon sweet spot takeaways.

THE BUSINESS CASE FOR LOW-CARBON BUILDINGS

Low-carbon buildings—low in both embodied carbon and operational carbon—offer a compelling value proposition for real estate owners, investors, and developers, encompassing environmental, economic, and social benefits. The ULI publications, *Embodied Carbon in Building Materials for Real Estate*[2] and *The Materials Movement: Creating Value with Better Building Materials*,[3] outline several dimensions of the return on investment for low-carbon materials as part of a real estate strategy.

BUSINESS CASE FOR LOW-CARBON BUILDINGS

INVESTOR AND TENANT DEMAND

Investors and tenants are prioritizing low-carbon buildings

POLICY COMPLIANCE

Building performance and embodied carbon standards are increasing

Low-carbon buildings reduce regulatory risk

LOWER OPERATING COST

Save on materials and labor costs

Reduce operational energy costs

Achieve green premium with enhanced asset value

Investor and Tenant Demand

Increasingly, investors and building tenants are considering building-related embodied and operational carbon emissions as a factor in new construction, leasing, and retrofits. For example, Caroline Johns, director of sustainability at Pembroke Real Estate Inc., leads portfolio strategy and implementation of the firm's sustainability efforts in 13 global markets in Europe, North America, and Asia. Asked about what's driving developers to consider carbon as part of their investment decisions—whether it is client driven, market position, or other regulatory considerations in the markets she operates in—she indicated it is

> *"all of the above. There's definitely increasing pressure from regulations in all of those markets to be as efficient as possible to contribute to the reduction of [greenhouse gas emissions reduction targets] in each of those cities. There's also increasing market pressure. There are tenants who will only occupy buildings that have a certain [green building] certification level or who expect a certain efficiency in the cost of their operating expenses and who want to align with purchasing renewable energy."*

Tenants and other building occupants increasingly track portfolio-level carbon emissions as part of their sustainability goals and internal and external reporting; investors' desire to gain insight into these data is also growing. Properties that can demonstrate lower life-cycle carbon emissions thus accrue an advantage and gain market position. Private equity investors are requesting data-driven science-based targets (SBTs)[4] tailored to a building and its context and to enterprise or corporate-level carbon emissions reduction targets.

Policy Compliance

Many governmental jurisdictions are beginning to regulate operational energy as well as carbon emissions associated with local fuel sources (such as bans on natural gas for new construction). Low-life-cycle carbon buildings can reduce regulatory risk, allowing tenants, owners, and developers to align their investments with public policy and global efforts to combat climate change. One example of government regulation is the building performance standard, New York Local Law 97,[5] which mandates substantial reductions in greenhouse gas emissions from buildings larger than 2,323 square meters (25,000 sq ft). It imposes carbon emissions caps and penalties for noncompliance, incentivizing property owners to invest in energy-efficient upgrades and sustainable practices. The legislation is integral to New York City's broader efforts to mitigate its environmental impact and transition to a lower-carbon built environment. Other localities regulating the embodied carbon of new developments include Oslo, Norway, and Vancouver, British Columbia, Canada, which regulate life-cycle carbon, as summarized by the Carbon Leadership Forum's Embodied Carbon Policy Toolkit.[6]

Lower Operating Cost

Economically, low operational carbon buildings present cost-saving opportunities that provide decades-long returns. Reduced energy consumption means lower utility bills, enhancing the overall financial performance of the property. As energy prices continue to rise and regulations favor sustainable practices, low-carbon buildings are likely to be more resilient and attractive to tenants, investors, and buyers, thereby enhancing the property's market value.

Moreover, lower embodied and operational carbon buildings can reduce both capital and operating costs. Andrew Bush leads Morgan Creek Ventures LLC[7] based in Boulder, Colorado, and has experience with sustainable new construction and renovation projects throughout North America; he is developing a new approach for carbon reduction he calls Prototype One. Bush says it involves

"rethinking all aspects of materials and labor, with cost ultimately being a critical driver of embodied carbon reductions. The goal is to—with a group of developers, architects, and structural mechanical engineers—look at how we can reduce material and labor input for a typical four-to-five-story, wood-frame multifamily building and aim for an embodied carbon reduction [that] is somewhere close to 25 or 30 percent."

DESIGNING FOR EMBODIED AND OPERATIONAL CARBON

The Carbon Sweet Spot: Understanding Tradeoffs between Embodied and Operational Carbon

The tradeoffs between embodied and operational carbon represent a complex balancing act, as both aspects contribute significantly to a building's life-cycle carbon emissions. The balancing act is especially important when designing the building envelope, which directly influences how much energy will be needed to heat and cool the building during its service life. Thus, the building envelope affects operational emissions as well as the emissions embodied in the facade materials.

The optimal level of investment in embodied carbon for operational carbon returns depends on the local climate, energy grid, and material supply chains. Given the long lifespan of buildings and building components, as well as changes in climate, energy grid carbon intensity, building technologies, and costs, this decision-making process includes many uncertainties. Decision-makers must consider different scenarios to assess which design choices will best suit a building over its service life.

Examples of some of these tradeoffs include the following:

- **Thermal Performance versus Embodied Carbon:** Increasing energy efficiency in operational aspects (heating, cooling, lighting) sometimes requires using more material, or material with higher embodied carbon content. For instance, increasing wall or roof insulation thickness may have a higher upfront embodied carbon footprint, but may yield lower net carbon emissions over the life cycle of the building due to energy efficiency benefits. Compliance with local codes or building performance standards, which may set requirements for energy efficiency or operational carbon emissions, also factors into this decision.

- **Technological Advancements:** Investments in advanced, energy-efficient technologies such as triple- or quad-pane window glazing may reduce operational carbon. But the additional glass layers require much more material, resulting in a higher embodied carbon footprint. Newer or unique technologies might also involve manufacturing processes with higher embodied carbon or be unavailable locally, increasing transportation-related carbon costs.

- **Low-Carbon Material Choices:** When designing a high-performance building envelope, opting for materials with lower product stage emissions (A1 to A3) or with a longer service life will reduce the tradeoff between embodied carbon investment and operational carbon savings. Sometimes these material choices can increase upfront costs or involve changes to a traditional design/build process; however, cost-comparable options are frequently available, and architects and general contractors are often able to incorporate the materials with proper planning.

- **Renovation and Retrofitting:** Reusing existing structures can significantly reduce embodied carbon by avoiding the embodied carbon associated with the building's structural components such as concrete and steel. However, renovating older buildings may require investments in new, more efficient heating, ventilation, and air conditioning (HVAC) systems and structural upgrades to extend the assets' service life and to meet code and operational energy requirements.

- **Window-to-Wall Ratios:** WWR is widely known to have a large impact on operational emissions, due to the lower thermal performance of glazing assemblies compared with wall assemblies. Thus, in most cases WWRs lower than 40 percent are recommended. However, depending on the materials and quantities in both assemblies, the embodied emissions of the wall could be significantly higher than those of the windows, as is the case in most curtain wall systems. In such cases, a lower WWR does not necessarily correspond to lower total life-cycle emissions.

A holistic understanding of these tradeoffs requires a comprehensive analysis of the specific context, project goals, and local conditions, and is a prerequisite for making informed decisions that align with project objectives. Striking a balance between embodied and operational carbon emissions is a crucial aspect of realizing the most building value with the least environmental impact.

For developers, the process for achieving that balance may look something like figure 3. Decisions around specific design elements and overall design strategies need to take into account an array of variables, such as local climates, energy grids, and carbon policies, and arrive at an approach that minimizes total life-cycle carbon with each of these processes in mind. (A deeper explanation of whole building life-cycle assessment can be found in the Case Studies section.)

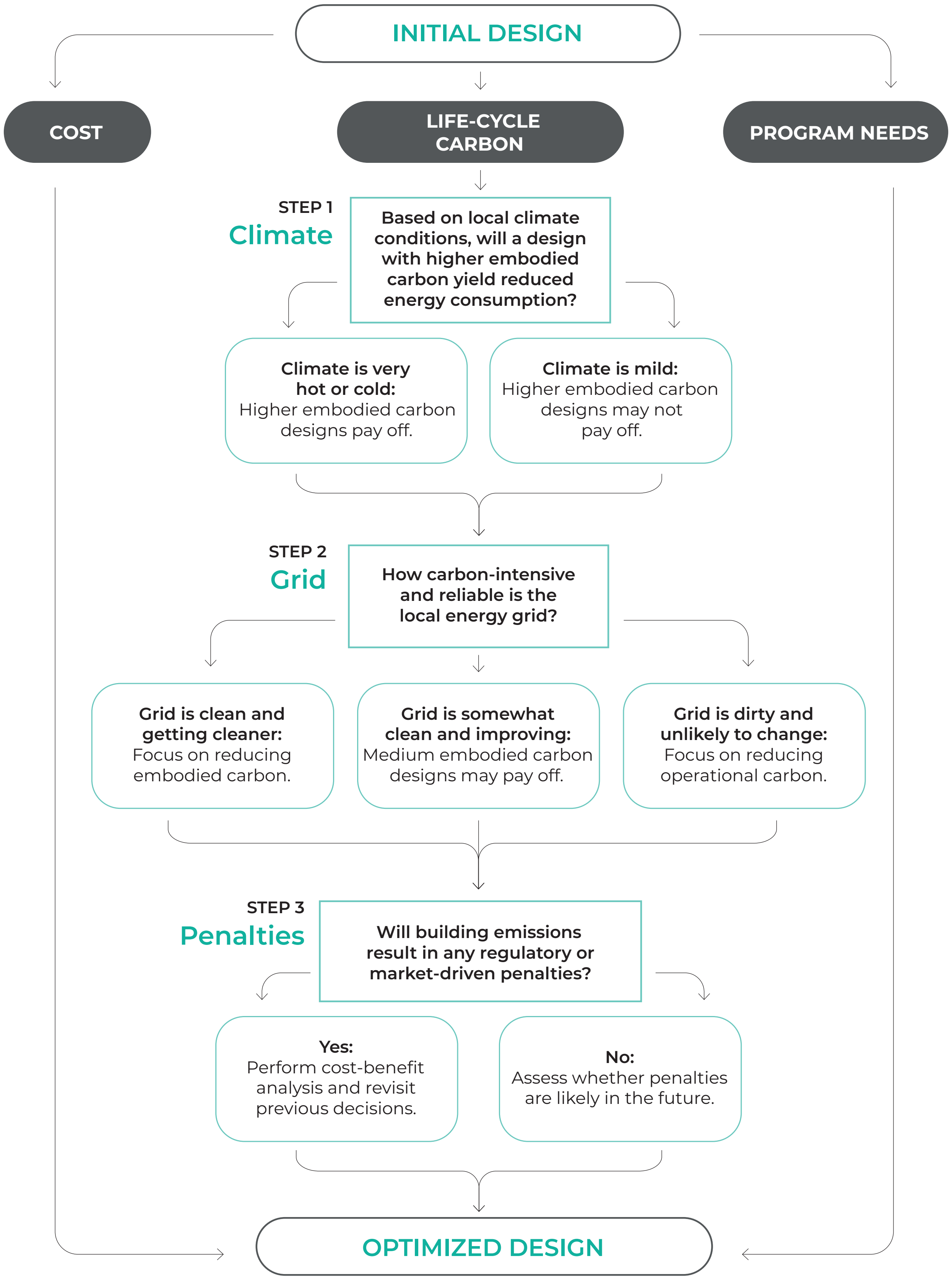

Building owners can analyze life-cycle carbon alongside considerations such as cost and programmatic needs.

FIGURE 3. Decision-making process to help developers find the carbon sweet spot and optimize both embodied and operational carbon over a building's life cycle, considering design, policy, and climate factors. Depending on these factors, increasing the embodied carbon of the building materials may or may not result in sufficient reduced operational carbon over the life cycle of the asset.

Sources of Carbon Emissions within Buildings: Why Focus on Facades?

In most buildings, the structure and envelope make up the majority of embodied carbon emissions; a smaller percentage relates to internal partitions and finishes.[8] Typically, the structure, internal finishes, and partitions have little effect on the operational performance of the building, and thus the embodied emissions from these components are largely unrelated to the operational emissions of the building.

In contrast, the building envelope plays a significant role in both embodied and operational emissions, meaning that carbon tradeoffs are particularly pronounced when related to the building envelope.[9] The insulation, windows, shading, framing, and cladding of a building can all play an important role in determining the energy use intensity of a given building, as can the mechanical HVAC system types and sizes required to ensure occupant comfort. For example, buildings in cold climates tend to use a high amount of insulation and might use triple glazing to reduce heating loads. Both these components increase the embodied carbon of a building. The result is a tradeoff between embodied carbon increases (or investments) at the initial construction of a building versus operational carbon reductions (or returns) in the form of low operational carbon emissions over the building's life cycle.

Building enclosure components are long-lasting, with a service life often exceeding 25 years, and they represent one of the costliest of all building systems. In addition, Duncan Cox, associate director at the building, consulting, and engineering firm Thornton Tomasetti, notes that embodied carbon in facades has often been undercounted.

"Historically there has always been a big focus on the embodied carbon of structures. We didn't really look at the facades. But then I started looking at some of our high-performance (operational) buildings, and I did a proper carbon [analysis] on the materials of that facade and realized it was coming out at 40 percent of the whole [life-cycle] carbon footprint, which was a big eye opener."

The building enclosure and facade design in a commercial office or mixed-use residential tower represents a nexus of several building value considerations: cost, comfort, aesthetics, views, energy efficiency, and—increasingly—embodied carbon and material sourcing. Key factors that must be addressed include window-to-wall area percentages, glass types, spandrel and insulation materials and assemblies, air tightness requirements, and the spacing and configuration of aluminum curtain wall frames.

The case studies of buildings in London, New York, and Singapore in the following section demonstrate how these investment decisions and tradeoffs affect whole life-cycle carbon, considering building designs, local climates, regulations, and energy grids.

CASE STUDIES: FINDING THE CARBON SWEET SPOT

Kohn Pedersen Fox provided the report team with architectural and energy modeling data for three real-world buildings in London, New York, and Singapore. The team analyzed the data with a “carbon sweet spot” lens, seeking to optimize the embodied and operational carbon tradeoffs in the design of new buildings. These assets are already sustainable in their own right, and this exercise is not intended to diminish their leadership and innovation. Instead, it is meant to provide hypothetical analyses to inform and inspire future whole life-cycle carbon considerations across the built environment. Furthermore, it aims to walk developers through the process of analyzing multiple factors, such as building design, local policy, energy grids, and climate, when considering design decisions that impact carbon emissions over their building’s lifetime.

Each case study includes a description of the project, context with respect to carbon-related local policy and climate zone, background on what was analyzed, and overall takeaways. As already discussed, the design tradeoffs come into play most prominently in the building facade.

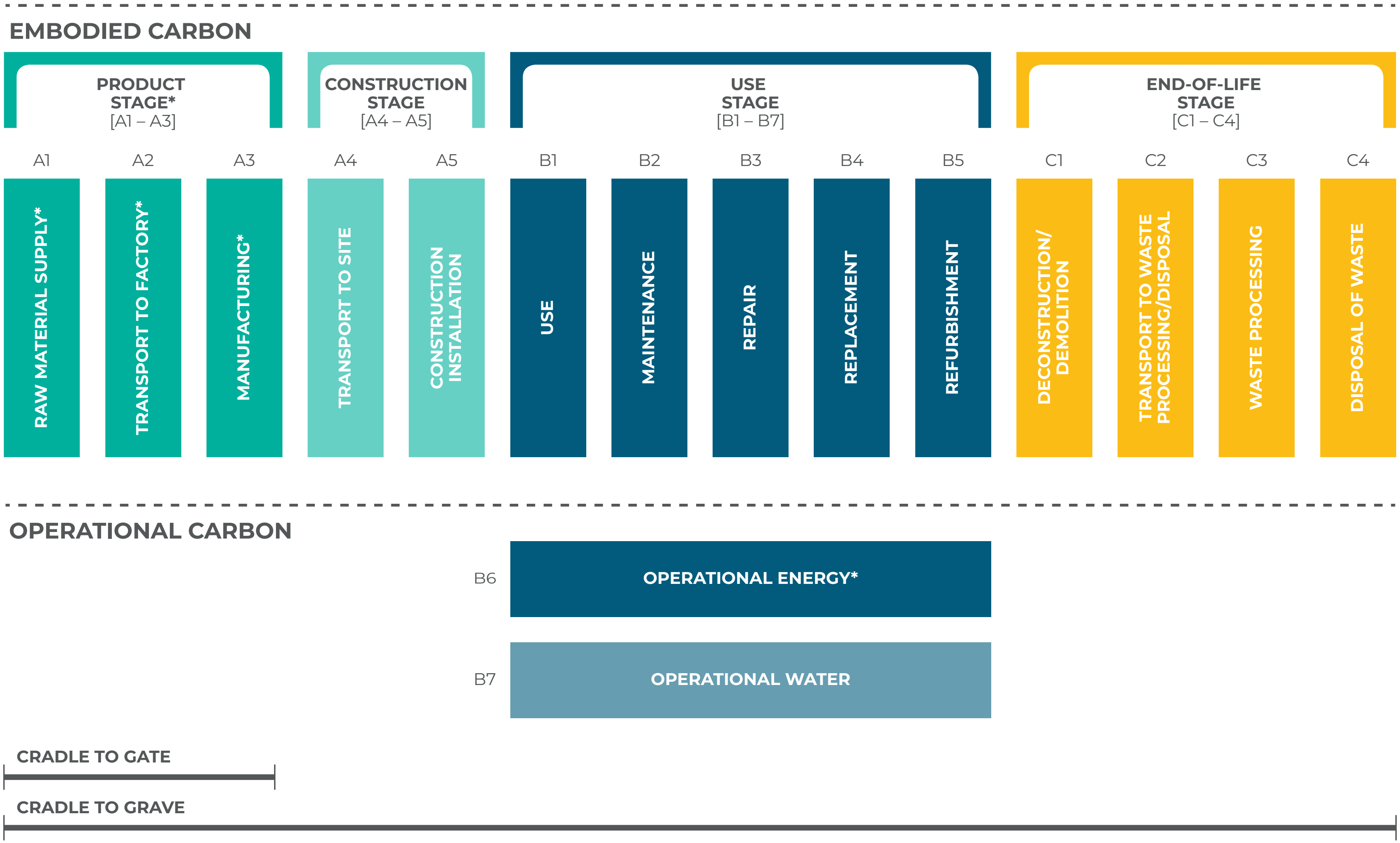
The three buildings examined for this report offer a glimpse into a variety of architectural design decisions, climate contexts, grid carbon intensities, and use types. One Crown Place in London was chosen to explore the effects of glass area and wall insulation on a residential building in a mild climate where electricity for heating and cooling is already low in carbon emissions. The One Vanderbilt office tower provided an opportunity to examine the effect of aluminum frame area and glass type in New York City’s moderately cold winters and hot summers with a high-carbon-intensity electrical grid that is slated to rapidly decarbonize. The 18 Robinson building, a mixed-use high-rise, is situated in the hot equatorial climate of Singapore; it served as the basis for investigating the life-cycle carbon impact of fixed shading elements in a cooling climate where building materials are typically sourced from significant distances.

How the Carbon Sweet Spot Was Evaluated

Traditionally, building professionals aimed to reduce the environmental impacts of buildings by minimizing operational energy consumption. In the 1990s, life-cycle assessment (LCA) methodology emerged, which aimed to quantify products' impact on the environment. In the realm of buildings and construction, these assessments revealed the no-less-significant impact of building materials on sustainability. Subsequently, whole building LCA (WBLCA) was developed to evaluate a building's environmental impacts across various life-cycle stages, from raw material extraction and manufacturing through construction, operation, maintenance, and eventual demolition. The life-cycle stages in WBLCA are shown in figure 4.

Carbon emissions serve as the primary metric for evaluating the environmental impact of buildings. Carbon emissions are measured in global warming potential (GWP), which represents the relative contribution of greenhouse gasses to global warming over a specified period compared with CO_2. The unit for quantifying GWP in this report is kilograms of CO_2 equivalent ($kgCO_2e$).

For the scope of this report, embodied carbon emissions include only the "cradle to gate" life-cycle stages (also known as A1–A3 or product stage emissions) shown in figure 4. These emissions are produced during the raw material extraction, transportation to factory, and manufacturing of building materials and assemblies. Operational carbon emissions (also known as B6 emissions) are the emissions produced from heating, cooling, and lighting.[10]



*LIFE-CYCLE STAGES INCLUDED IN ANALYSIS

FIGURE 4. Life-cycle stages for WBLCA based on international standards EN15978 and ISO 21931.

Most WBLCA standards share a similar methodological framework, which includes defining the object of study, estimating quantities of materials, and quantifying operational energy use. Ultimately, the environmental impacts are calculated at different life-cycle stages using environmental product declarations, the U.S. Life Cycle Inventory Database, or emission factors. The process used to conduct the WBLCA analysis for this report is shown in figure 5 and outlined on the following page.

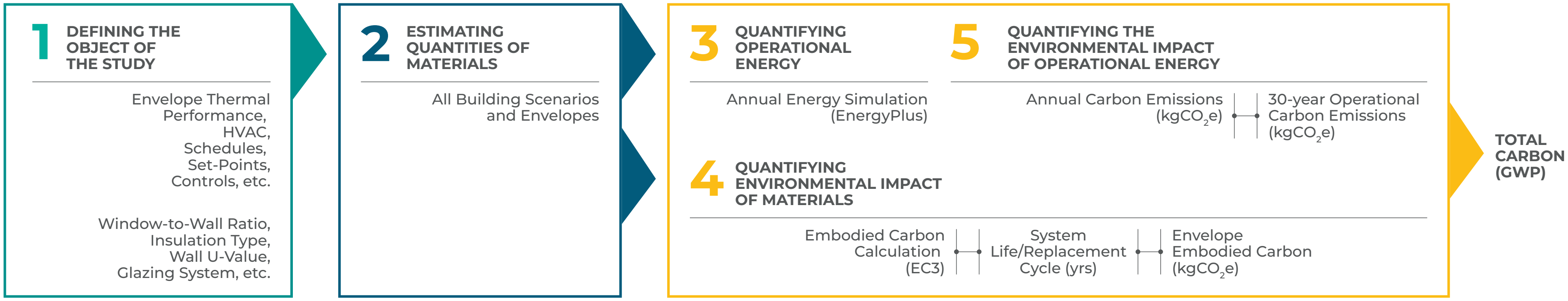


FIGURE 5. Process diagram for calculating building life-cycle embodied and operational carbon.

Steps for Calculating Building Life-Cycle Embodied and Operational Carbon

1

Defining the Object of Study

The object of study in a WBLCA is defined by the functional unit (also called functional equivalent); it is a series of parameters that “provide a basis to ensure comparability of the assessment results of different buildings and design solutions” (ISO 219311-1:2022). The functional unit can include the building use type, gross floor area, total height, number of stories above and below grade, occupancy patterns, expected service life, climate zone, and structural type.[11] This step also involves specifying which building elements and assemblies are in and out of the scope of the analysis.

2

Estimating Quantities of Materials

For this report, material quantities in the facade were estimated using a combination of three-dimensional geometric modeling software, spreadsheet tools, and manufacturer data.[12]

3

Quantifying Operational Energy

Energy models were created for each unique facade configuration studied in this report. Annual energy use consumption by end-use (heating, cooling, and lighting) and peak cooling and heating information were collected for each simulation.

4

Quantifying Environmental Impact of Materials

Embodied carbon impacts were calculated using the Embodied Carbon in Construction Calculator (EC3) tool. Created by the nonprofit Building Transparency, EC3 provides users with embodied carbon data from environmental product declarations to measure and compare the carbon footprint of construction materials.[13]

5

Quantifying the Environmental Impact of Operational Energy Use

The carbon emissions related to operational energy use were calculated using the annual energy consumption from energy models, multiplied by the carbon intensity of the local electricity grid and its anticipated annual decarbonization rate over 30 years.

Uncertainties in This Analysis

Buildings have long and unpredictable service lives and are made up of materials and systems that come from disconnected industries and geographically dispersed supply chains.[14] The complexity of buildings can render WBLCA results unreliable if factors that create variability are not acknowledged. Studies have shown that the variability of WBLCA results coming from uncertainties are substantial, and not accounting for these uncertainties can make the comparison between different design options misleading or even meaningless.[15]

Types of uncertainties include the following:

- **Data Uncertainty:** Data quality is a significant source of uncertainty. Environmental impact data, such as material manufacturing processes, transportation emissions, and energy consumption, may not always be accurate. Variations in data sources and the completeness of data can introduce uncertainty.
- **System Boundaries:** Defining the boundaries of the assessment, including which life-cycle stages and environmental impacts to consider, can be subjective. System boundaries need to be clearly articulated to understand the scope of analysis and contextualize the results.
- **Variability in Building Operations:** Predicting future building operations, energy consumption, and maintenance practices is challenging. Changes in occupant behavior, climate conditions, and technological advances all introduce uncertainty.
- **Location and Regional Variation:** The environmental impact of materials and energy sources can vary significantly by region. Accounting for regional variations in the assessment can be complex and introduce uncertainty, especially for global projects.
- **End-of-Life Assumptions:** The environmental impact of disposal, recycling, or deconstruction processes can vary based on the available technology and market conditions at the end of a building's life, which is hard to predict with certainty.
- **Future Technological Advances:** The introduction of more sustainable building materials, construction practices, and energy sources can significantly affect the accuracy of WBLCA assessments. Predicting these advancements introduces uncertainty.

One Crown Place, London, preserves historic buildings, renovates a mid-rise office, and adds new residential towers.

TMNIKONIAN COURTESY KPF

ONE CROWN PLACE, LONDON

IMPACTS OF GLASS AREA AND WALL AND WINDOW PERFORMANCE IN A LOW-CARBON GRID

SUMMARY OF CASE STUDY

LOCATION: London

BUILDING TYPE: Mixed-use, mid-to-high-rise, with preserved Georgian terraces, a renovated 1970s office, and new residential towers.

CARBON CONTEXT: London has ambitious decarbonization goals, energy policies for buildings that focus on Energy Performance Certificate ratings and requirements for low-carbon design, and a clean energy grid that supports high-performing buildings and emphasizes reducing embodied carbon.

CLIMATE CONTEXT: Temperate, with mild and consistent weather year-round, supporting passive design measures to reduce energy use.

TRADEOFFS ANALYZED: Impacts on life-cycle carbon of WWR, double versus triple glazing, and wall insulation level.

TAKEAWAYS: In this context, WWR has largest impact on carbon, and window area can be minimized as practical; triple glazing significantly increases life-cycle carbon because embodied emissions rise significantly while operational emissions do not decrease substantially; increasing wall insulation from RSI 3.5 (R-20) to RSI 5.3 (R-30) provides only modest life-cycle carbon reductions for the same reason.

DESCRIPTION

One Crown Place is a 256,000-square-meter (607,000 sq ft) regeneration project in the London Borough of Hackney. It preserves local historical character within a new mixed-use development. The project offers 246 new living units with an array of amenities, including retail spaces, a boutique hotel, and offices. Respecting the area's heritage, a locally listed Georgian terrace was renovated, while a 1970s office block was reimagined to meet contemporary standards. In addition, the adaptive use of a Victorian warehouse avoided demolition while bridging historical elements with a six-story podium and residential towers.

One Crown Place delivers a high-quality user experience and energy-efficient operations across a range of space-use types. Power to the development is supplied by a centralized energy center that distributes loads between multiple uses and helped achieve a 25 percent reduction in operational carbon emissions through heat recovery and a rating of BREEAM Excellent for the office. The facade design optimizes the amount of glazing and provides operable windows to reduce summer overheating and maximize energy efficiency. During construction, all demolition waste was recycled and 100 percent renewable energy was used. To reduce embodied carbon in the structure, GGBS (ground granulated blast-furnace slag) cement replacement was used in reinforced concrete structural elements and steel contained 20 percent recycled content.

Architecturally, the new structures vary in height, featuring facades that harmonize with and stand out against the historical context. Glazed terra-cotta on external facades pays homage to the area's prevalent masonry and glazed-brick buildings. Internally, custom screen-printed glass panels contrast with the terra-cotta, reflecting Hackney's tradition of craftsmanship.

TAKEAWAYS FOR DEVELOPERS

In searching for carbon sweet spots using the design of One Crown Place, this report identifies key data points that, though not universal, can inform building decision-makers seeking to reduce life-cycle carbon as part of facade design:

Window Area

- WWR significantly affects carbon emissions, especially in heating-dominated climates: the larger the WWR (meaning more window area per wall), the more total carbon emitted. WWR can be minimized as much as possible while balancing daylight and view requirements.

Triple Glazing

- In London, the addition of triple glazing can result in more embodied carbon emissions than it saves in operational carbon.
- When using triple glazing in any climate, sourcing glazing units with low embodied carbon (from manufacturers) is an important consideration to minimize impact on total emissions.

Wall Insulation

- Increasing the insulation level of the wall assembly from RSI 3.5 (R-20) to RSI 5.3 (R-30) through the addition of continuous rigid insulation leads to greater embodied carbon emissions compared to the operational carbon it saves.
- When deciding on insulation type for a wall assembly, the embodied carbon of the insulation material can be considered to reduce overall emissions. Rigid insulation generally emits more embodied carbon per RSI or R-value, though this can vary significantly between manufacturers.

CARBON CONTEXT

The United Kingdom, and London in particular, has developed ambitious decarbonization goals in the building sector. In 2022, the mayor's office released a set of pathways for how the city could become a zero-carbon city by 2050.[16] Currently, electricity emissions in London are approximately 0.152 $kgCO_2e$ per kilowatt-hour (kWh).[17] This compares with 0.207 $kgCO_2e$ per kWh for the United Kingdom overall. The London spatial development strategy, known as the London Plan, includes a strategic road map for carbon reduction in buildings. The plan sets targets for carbon emissions reduction, energy efficiency improvements, and renewable energy generation in new developments across the city; it also requires accounting for the embodied carbon associated with existing building demolition.

The United Kingdom also has an established building energy transparency program through the use of required Energy Performance Certificates (EPCs). EPC ratings are required for most buildings throughout the country when they are sold, rented, or constructed. The certificates provide information about the energy efficiency of a building, including its carbon emissions, and recommendations for improvement. EPC ratings influence property transactions and can incentivize building owners to invest in energy efficiency measures, particularly with proposed legislation, such as the Minimum Energy Efficiency Standards, on the horizon.

Duncan Cox, associate director at the global engineering consultancy Thornton Tomasetti's London office shares that

"buildings over a certain size in London have to have both a whole [life-cycle] carbon assessment and a circular economy assessment—so you have to quantify all the building materials and where those waste streams are, whether you can retain or you reuse elsewhere—and the idea is to divert from the landfill."

Detailing the reporting requirements, he adds,

"That's the first phase of the circular economy narrative where [a building owner has] to talk about how [they're] designing in layers, designing for future adaptability and dismounting, and also using recycled elements."

Each of these developments is increasing the prominence of life-cycle carbon in real estate decision-making.

The low-carbon intensity of London's electricity grid and decarbonization goals amplifies the relative impact of embodied carbon emissions compared with operational carbon emissions.

CLIMATE ZONE CONTEXT

London’s temperate maritime climate is characterized by mild temperatures and moderate rainfall. The climate is influenced by its proximity to the Atlantic Ocean and the presence of the Gulf Stream, which helps to moderate temperature extremes. This makes it particularly well suited for passive thermal design measures (using the building structure itself, rather than HVAC systems) to improve building performance. Many of these strategies rely on the performance of facade elements to reduce the need for heating, cooling, and lighting. In this climate, preventing heat loss through the facade is the most impactful passive design strategy. The key is to optimize the WWR to prevent heat loss through glazing. Reducing the air infiltration through the facade and improving the RSI or R-value of the facade also prevents heat loss and reduces total energy consumption related to space conditioning.

ANALYSIS: WINDOW-TO-WALL RATIO, GLASS TYPE, AND INSULATION TRADEOFFS

In recent years, emphasis has been on reducing window-to-wall ratios as an efficiency strategy. At the same time, countervailing priorities for daylight and views, as well as aesthetic concerns of facade appearance and marketability, have driven designers to increase glass areas. Concurrently, designers have sought to improve the performance of exterior walls by increasing the amount and performance of insulation in the nonwindow area of walls.

When viewed through the lens of operational energy, a building envelope with a low WWR will typically outperform one with more window area. However, when viewed through a life-cycle carbon lens, the picture becomes more complex.

Increased insulation thickness and the additional material needed to accommodate a thicker wall assembly can increase embodied carbon in the envelope; the use of high-performance glass systems with lower embodied carbon can balance out these carbon-intensive wall assemblies. The carbon intensity of the heating energy source (e.g., fossil fuels versus cleaner electricity) can also have an outsized effect on this tradeoff. Notably, increased air tightness (which can be accomplished with tighter construction and improved detailing) can also decrease operational carbon emissions with modest impact on embodied carbon, reducing the need for more wall insulation.

One Crown Place was used to study the envelope WWR, glazing type, and wall insulation. The analysis evaluated the operational and embodied carbon emissions of 12 different envelope configurations shown in figure 6.

The resulting carbon emissions were separated by sources (i.e., glazing, insulation, framing, heating, cooling, etc.) to better identify the source of reductions or increases. The operational carbon emissions correspond to a 30-year operation cycle, and the embodied emissions do not account for any replacement of any building component for this period. The embodied carbon estimation only accounts for envelope components and does not include the building structure, finishes, or systems.

ONE CROWN PLACE

One Crown Place in London was used as the context to study the life-cycle carbon impact of 12 different configurations of window-to-wall-ratio, glass type, and wall insulation.

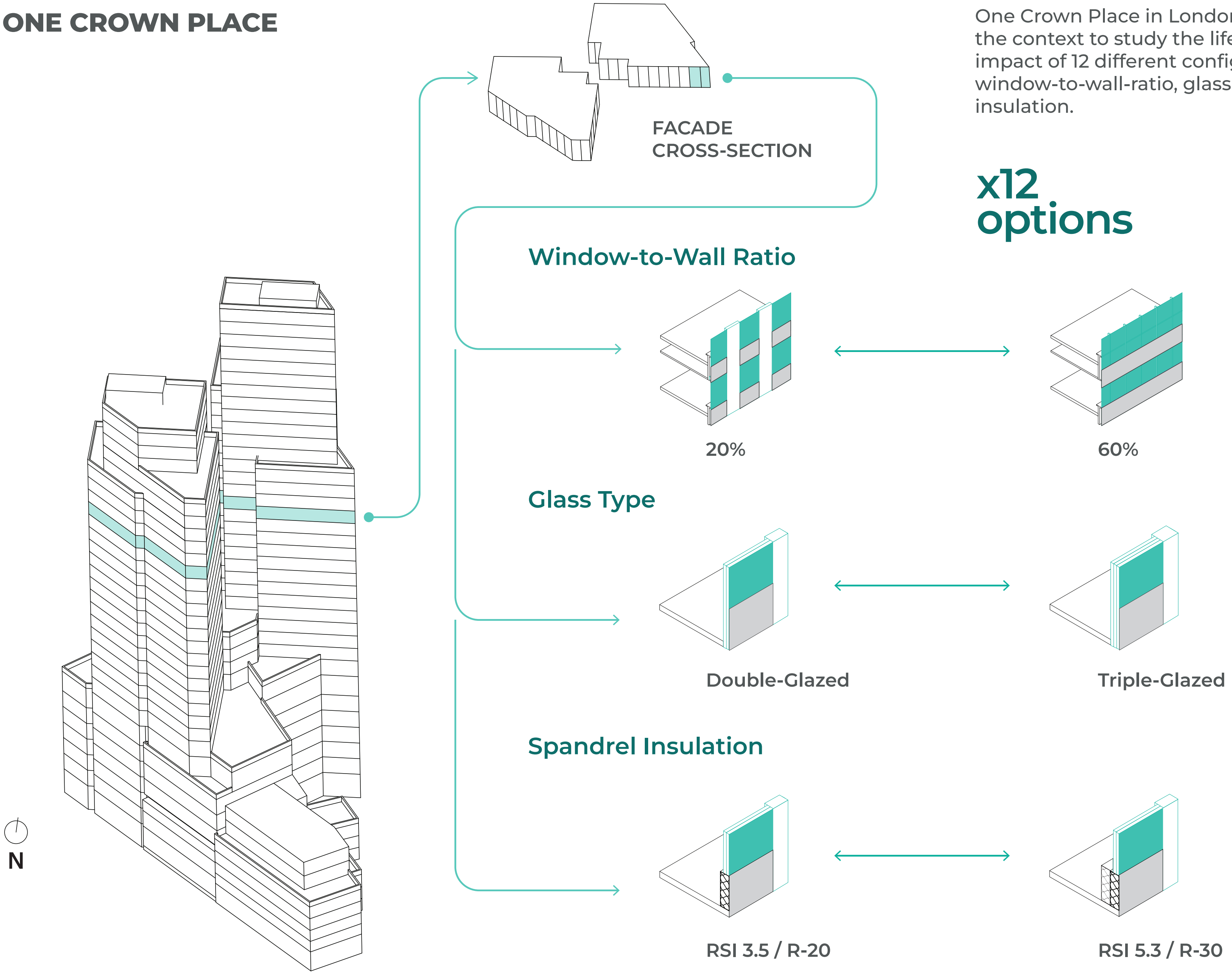


FIGURE 6. Diagram of three facade parameters studied at One Crown Plaza: (1) WWR, (2) glass type, and (3) insulation level in wall.

THE SWEET SPOT FOR ONE CROWN PLACE: OPTIMIZING THE WINDOW-TO-WALL RATIO

Figure 7 shows the 30-year embodied and operational carbon emissions for each configuration. The results are summarized below:

- Higher WWRs (resulting in more glass usage) increase both embodied and operational emissions, highlighting the importance of containing glazing as much as possible.
- Using triple- versus double-pane windows reduces the need for mechanical heating, thus reducing the operational carbon emissions. But the savings in operational carbon when using triple glazing do not outweigh the considerable embodied carbon required to produce triple-glazed windows given London's carbon context and cleaner electricity (see figure 8). From a total life-cycle carbon perspective, these results suggest that using triple glazing in this instance is difficult to justify. However, if a particular manufacturer can demonstrate smaller deltas between the embodied emissions of double versus triple glazing, then using triple-glazed windows may be a reasonable choice, particularly in buildings with higher WWRs.
- Using RSI 5.3 (R-30) versus RSI 3.5 (R-20) insulation in the wall reduces heat loss. This change reduces the need for mechanical heating, thus reducing the operational carbon emissions. However, the increased embodied carbon investment of adding the rigid insulation results in no total carbon savings. This is largely due to London's relatively clean electricity grid, which diminishes the savings in operational carbon in a total carbon context (see figure 9).

HUFTON + CROW, COURTESY KPF

AT ONE CROWN PLACE: MINIMIZING WINDOW-TO-WALL RATIO HAS GREATER IMPACT ON TOTAL CARBON THAN GLAZING TYPE AND WALL INSULATION

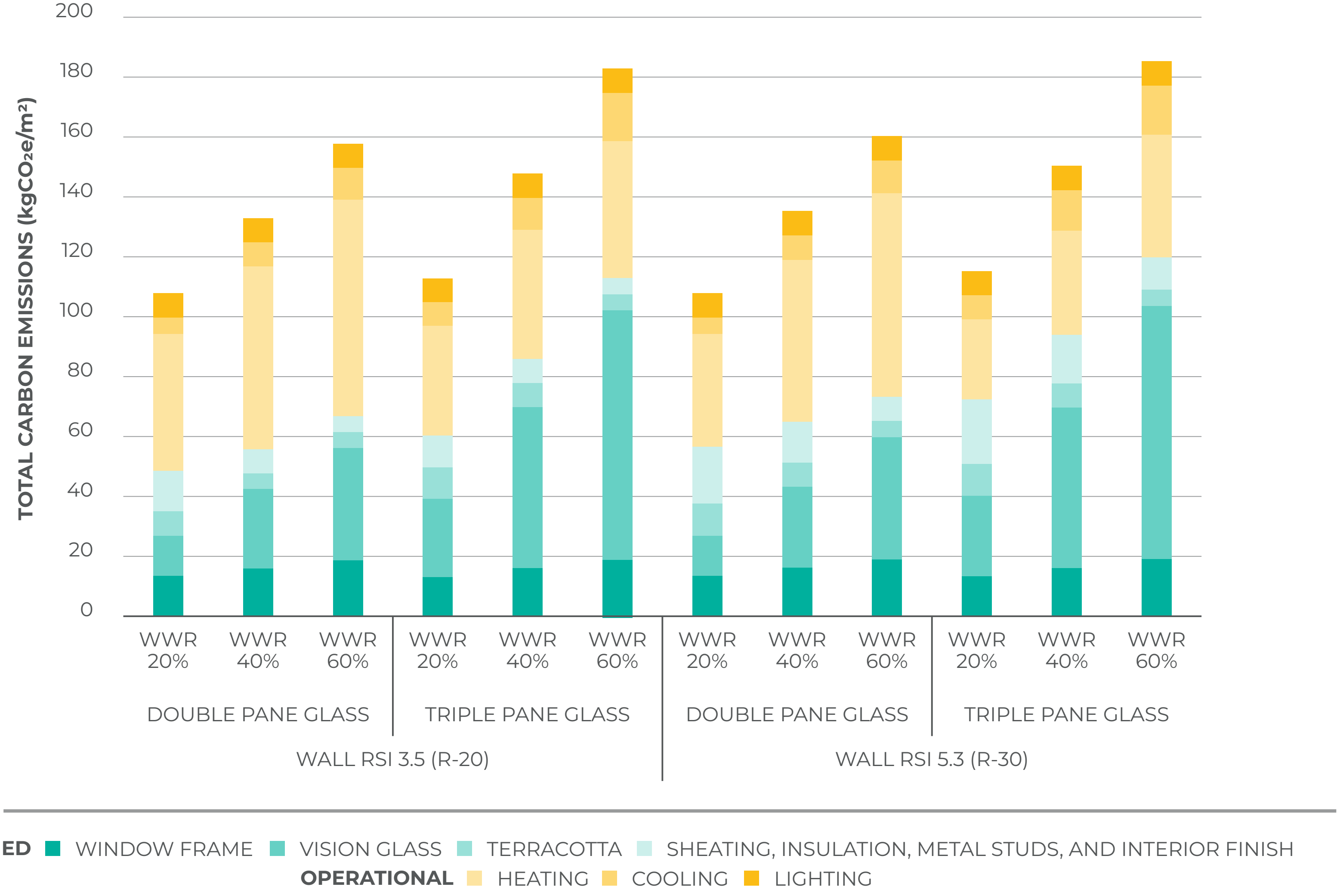


FIGURE 7. One Crown Place study results showing embodied and operational carbon emissions for a 30-year period for all tested variables (WWR, glazing type, wall insulation), assuming an electricity grid that reduces emissions by 3 percent each year. Of all the variables studied, results show that varying the WWR has the largest impact on total carbon emissions.

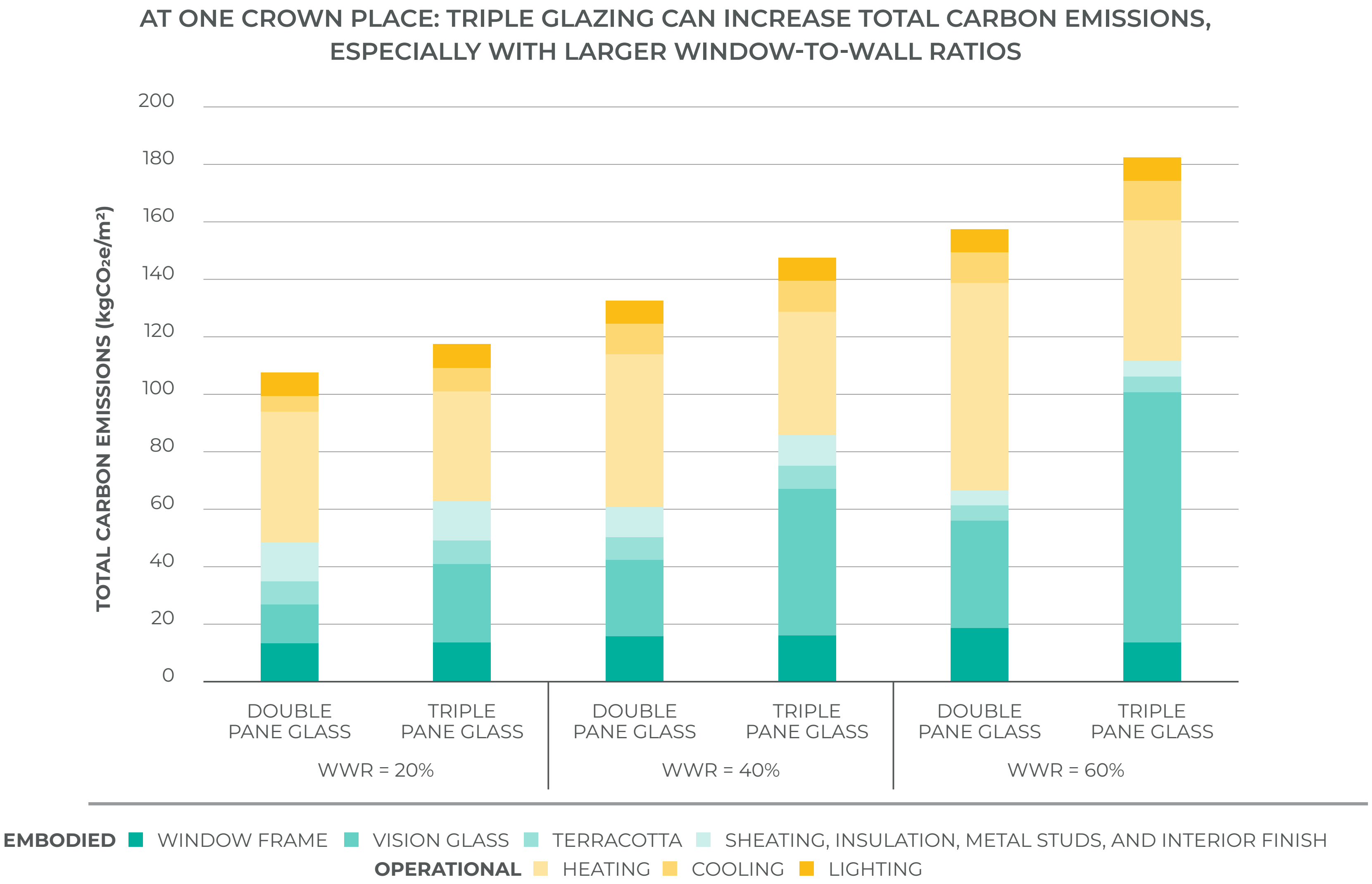
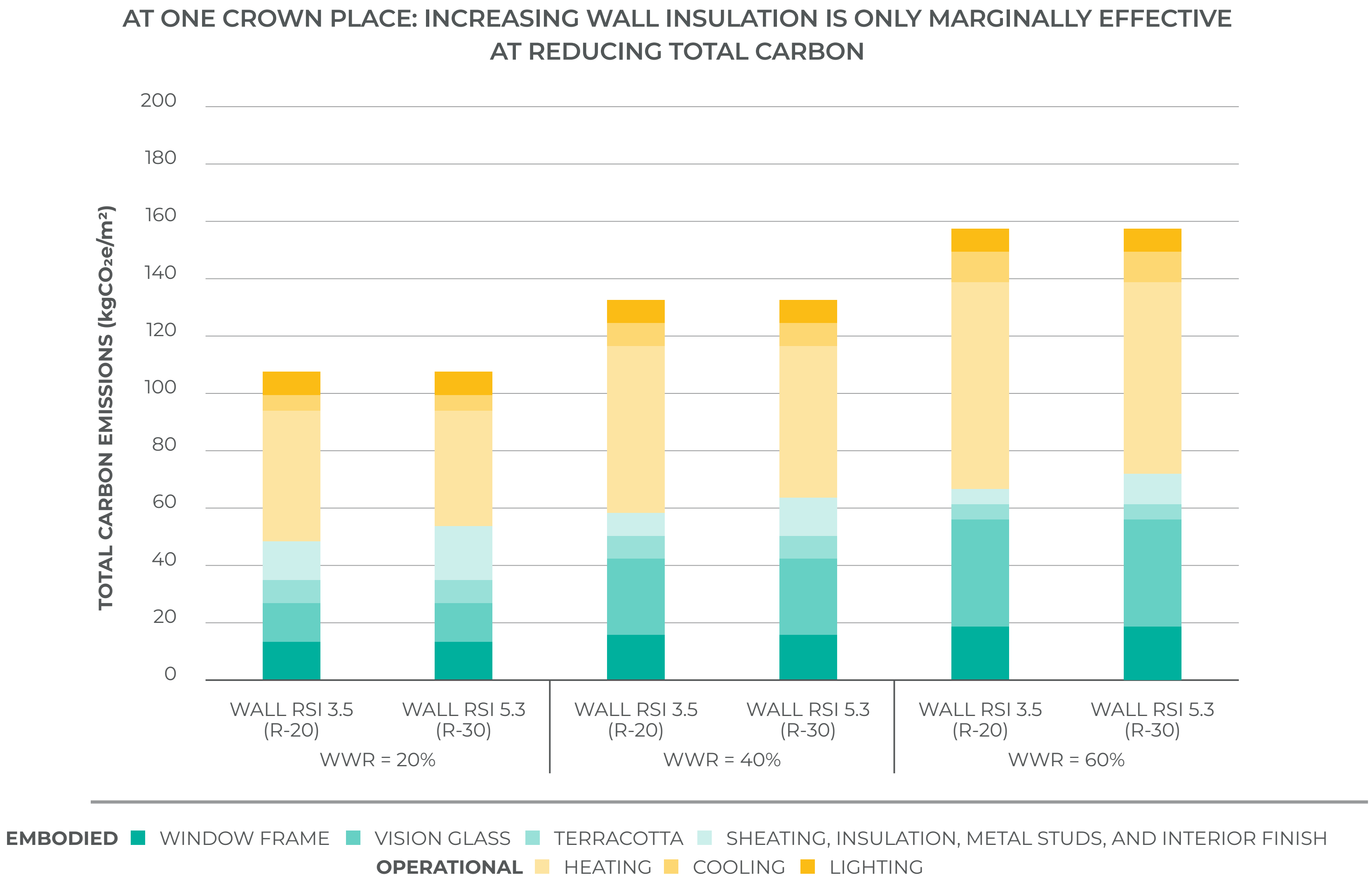


FIGURE 8. One Crown Place study results showing embodied and operational emissions for a 30-year period, using RSI 3.5 (R-20) wall insulation and varying WWR and glazing type (double-pane versus triple-pane), assuming an electricity grid that reduces emissions by 3 percent each year. Results show that total carbon emissions are always higher when using triple glazing, and the difference increases significantly with larger WWRs; however, WWR has a larger impact than glazing type on total emissions.



AT ONE CROWN PLACE: INCREASING WALL INSULATION IS ONLY MARGINALLY EFFECTIVE AT REDUCING TOTAL CARBON

FIGURE 9. One Crown Place study results show embodied and operational emissions for a 30-year period, using double-pane glazing and varying WWR and wall RSI/R-values (RSI 3.5/R-20 versus RSI 5.3/R-30), assuming an electricity grid that reduces emissions by 3 percent each year. Results show only a marginal difference between total carbon emissions for RSI 3.5 versus RSI 5.3 in all WWR scenarios, indicating that keeping window area down reduces carbon more effectively than increasing insulation in this case.


One Vanderbilt rises above the New York City skyline.

RAIMUND KOCH, COURTESY KPF

ONE VANDERBILT, NEW YORK CITY

HIGH-RISE OFFICE UNITIZED CURTAIN WALL IN A TEMPERATE CLIMATE

SUMMARY OF CASE STUDY

LOCATION: New York City

BUILDING TYPE: High-rise office tower

CARBON CONTEXT: New York City's grid is only slightly cleaner than the U.S. average, but strict city building decarbonization policies and state goals for clean energy by 2040 indicate that building and grid emissions will need to drop over time, supporting a blend of embodied and operational carbon reduction measures.

CLIMATE CONTEXT: Cold winters and warm summers, meaning buildings require significant heating and cooling energy throughout the year, enhancing the need for high-performance envelopes to preserve interior environments.

TRADEOFFS ANALYZED: Impacts on life-cycle carbon of curtain wall specifications (mullion spacing and size of glass panels), double versus triple glazing, insulation level of spandrel panels, and WWR.

TAKEAWAYS: In this context, increasing the spacing of mullions and using larger glass panels can significantly reduce carbon; triple glazing should be carefully assessed as embodied carbon increases may exceed operational carbon savings; and less glass area (WWR of 50 percent versus 65 percent) and increased insulation of spandrel panels provide only minimal life-cycle carbon reductions.

DESCRIPTION

One Vanderbilt stands out on the skyline as a super-tall skyscraper in Midtown Manhattan, reaching a height of 427 meters (1,401 ft) with 77 stories. Its modern design complements the urban fabric, serving as a beacon for Grand Central Terminal and the surrounding area. Its massing consists of four interlocking and tapering volumes that spiral toward the sky, presenting a visually striking form in dialogue with the nearby Chrysler Building. At the base, strategically angled cuts in the building mass reveal the long-obstructed view of the Vanderbilt corner of Grand Central Terminal's iconic cornice. At the body of the tower, the tower tapers to increase the sky view angle of the streets below to maximize access to daylight for pedestrians. Visitors to the building benefit from a car-free, pedestrian-only Vanderbilt Plaza, and a public transit hall provides access to Grand Central Terminal, the East Side Access, SUMMIT One Vanderbilt, Le Pavillon, Joji, and Épicerie Boulud.

One Vanderbilt has achieved LEED v3 Platinum and WELL Platinum certification, showcasing its commitment to energy efficiency and environmental design. The building incorporates diverse features focused on reducing carbon and improving the well-being of its occupants; these features include an advanced air filtration system, substantial glazing for natural light, and a high-performance building envelope. To maximize resilience and in line with the most advanced mechanical-electrical-plumbing solutions of its time, the building combines high-efficiency chillers with heat recovery and a cogeneration plant that produces heat as a by-product of the on-site production of electricity. As a result, the building reduced its energy use by 20 percent beyond the LEED baseline.

One Vanderbilt's modern workspaces offer daylight and views among other amenities to meet the needs of contemporary businesses focused on environmental quality and employee well-being. The building represents a harmonious blend of architectural innovation, sustainability, and functional design, making it a standout feature in New York City's urban landscape.

TAKEAWAYS FOR DEVELOPERS

One Vanderbilt offers an ideal context to identify carbon sweet spots in the design of unitized curtain walls for high-rise construction in New York City. Key carbon trend lines and takeaways include the following:

Curtain Wall Module Sizes

- Increasing curtain wall module sizes reduces total emissions by reducing (1) operational emissions by minimizing thermal bridging and air infiltration, and (2) embodied emissions by minimizing the number of aluminum mullions used between each glass piece.
- Expanding the module spacing—in this case, doubling from a 1.52-meter (5 ft) to a 3-meter (10 ft) module spacing—can reduce total emissions by 11 percent.

Triple Glazing

- In this case, the addition of triple glazing can result in more embodied carbon emissions than it saves in operational carbon.

CARBON CONTEXT

The average decarbonization rate of the U.S. electrical grid is currently approximately 3 percent per year.[18] New York State, which is primarily served by the Upstate New York electrical distribution subregion, has relatively low electricity-related carbon emissions: 0.105 kgCO_2e/kWh compared with a U.S. average of 0.386 kgCO_2e/kWh.[19] This is due to clean hydroelectric power generated in northern New York and in Quebec. However, the fuel mix for New York City is more complex. According to the Mayor's Office of Climate and Environmental Justice, carbon emissions associated with electricity serving Manhattan average 0.370 kgCO_2e/kWh, just below the national average, due to a continued reliance on 24 in-city power plants that run on natural gas and/or fuel oil and which provide nearly half of the city's electrical power.[20]

Given the city's reliance on fossil fuel for much of its electricity, tradeoffs between embodied and operational carbon are weighted in favor of reducing operational energy consumption. However, this calculation is likely to change over the life of a building built today because New York State has committed to 100 percent zero emissions electricity by 2040 under the Climate Leadership and Community Protection Act of 2019.[21]

New York City also has stringent regulations in place for the carbon performance of buildings. Known as Local Law 97 (discussed in The Business Case for Low-Carbon Buildings), this legislation limits how much carbon can be emitted by large buildings before fines are applied. These limits will become stricter over time.

CLIMATE ZONE CONTEXT

The climate in New York City is characterized by cold winters and warm summers, which means buildings require significant energy for heating and cooling throughout the year. This climate, along with New York's building codes, favors passive design strategies that minimize heat loss in the winter and heat gain in the summer. These strategies include lowering the window-to-wall ratio, increasing air tightness, increasing thermal performance of the envelope, and minimizing solar gains in the summer. Each of these variables can be considered in an envelope carbon tradeoff analysis.

ANALYSIS: UNITIZED CURTAIN WALL MODULES, GLASS TYPES, SPANDREL INSULATION, AND WWR TRADEOFFS

One of the key drivers of operational and embodied carbon is the construction and configuration of key facade elements—particularly the number of glazing units (glass panes), spacing or distances between mullions (aluminum framing elements), and the performance of spandrel panels (opaque insulated glass panels). These elements interact to determine thermal performance, air infiltration from outdoors, and the overall embodied and operational carbon associated with a unitized curtain wall system design.

The mullion spacing is particularly significant as it determines the amount of aluminum used, the number of glazing joints, and overall thermal performance (U-value). Aluminum can be minimized as it has a high embodied carbon cost and often drives total emissions. When the number of glazing joints is high, the envelope loses air-tightness and performs more poorly as a thermal barrier, losing heat and causing operational emissions to rise.

These issues are front-of-mind for New York-based KPF director, Nicole McGlinn-Morrison.

"We've been thinking more about curtain wall mullion module size. This started out not from a carbon reduction standpoint, but from the perspectives of energy performance and quality of the interior space. [Achieving these priorities] meant going to a larger-format glass."

Discussing carbon-related drivers for facade design, Bob Graustein, director at KPF's New York office, adds,

"If, for example, you go to 10-foot [3 m] glass versus a 5-foot [1.52 m] module, you get less aluminum, you get fewer breaks in the facade, better performance, the buildings are a bit tighter [from an air-leakage standpoint]; and then the byproduct of that is cost [reduction], which is just less framing and less waste on glass."

Similarly, Carlos Cerezo Davila, KPF's sustainable design leader and director, notes,

"The push for less carbon is also a push for less cost. Currently as architects, as life-cycle carbon becomes central to our decision-making, we need to make a compelling argument to incorporate envelope components that contribute to the aesthetic value of the building."

Regulations are also playing into major design decisions in commercial facades, especially where projects are seeking larger glass areas to improve views and building transparency. Cerezo Davila adds,

"Current New York City energy codes already require that if you go over a 45–50 percent window-to-wall ratio, you need to rely on triple glazing. There's no way around it, and in London or Boston you're in a similar situation."

A higher frequency of mullions increases cost, fabrication effort, and material associated with the net glazing area due to an increased number of insulated glazing unit (IGU) edges relative to the glass area. However, above certain dimensions, large panes of glass can cost more and be more challenging to install. They can also be more challenging to source and, depending on the project location, require shipping from greater distances, which increases cost and transportation-related embodied carbon emissions.

One Vanderbilt was used as the context to study facade mullion spacing, as well as glass type, amount of spandrel insulation, and WWR. The specific facade variables evaluated in this analysis of embodied and operational carbon are shown in figure 10.

ONE VANDERBILT

One Vanderbilt in New York City was used as the context to study the life-cycle carbon impact of 40 different configurations of facade mullion spacing, glass type, spandrel insulation, and window-to-wall ratio.

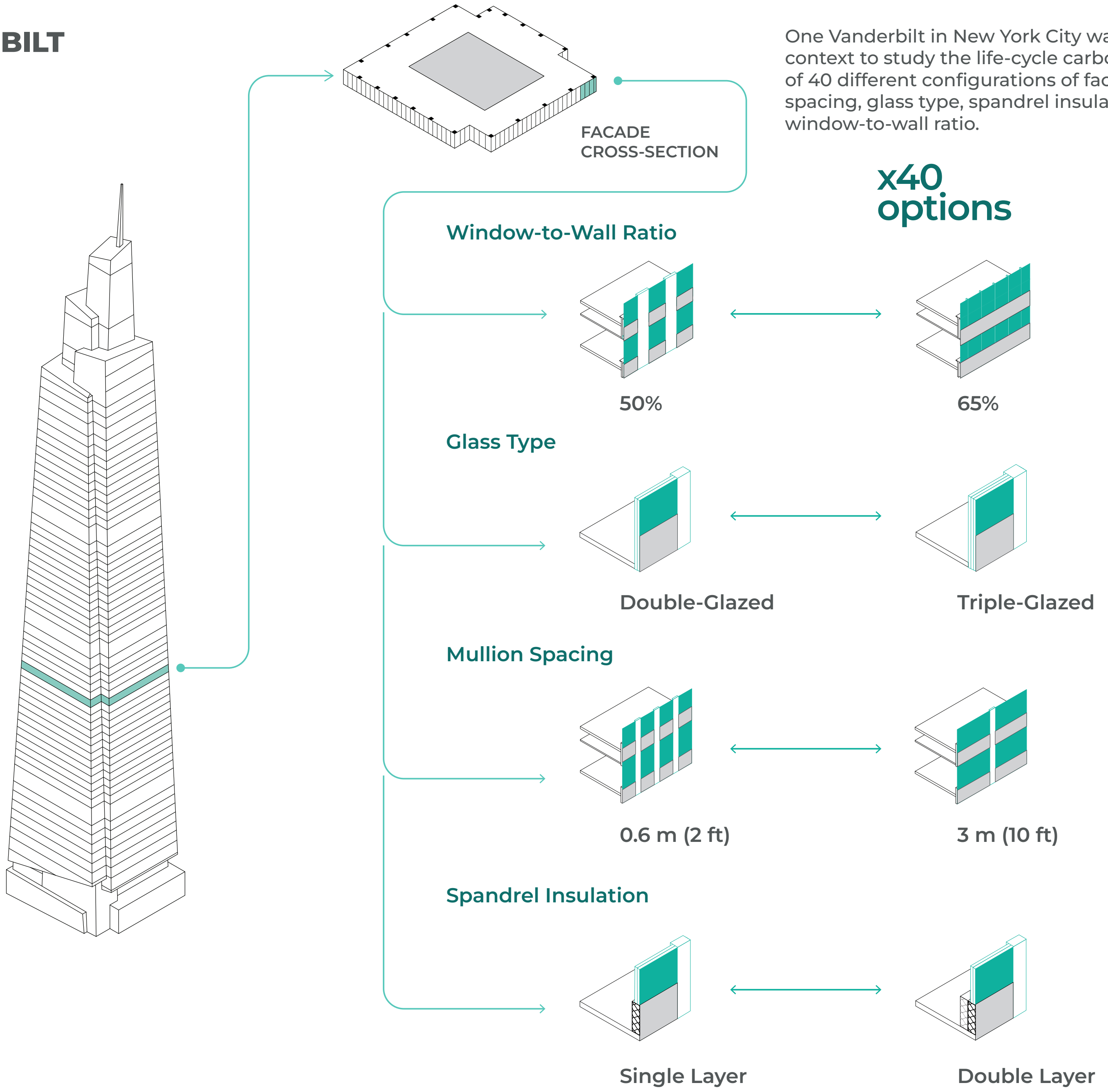


FIGURE 10. Diagram of the four facade parameters studied at One Vanderbilt: (1) mullion spacing, (2) glass type, (3) spandrel insulation, and (4) WWR.

THE SWEET SPOT FOR ONE VANDERBILT: OPTIMIZING MULLION SPACING

For building design and real estate decision-makers seeking to optimize life-cycle carbon in their facade design decisions, a few key takeaways include the following:

- Increasing the space between mullions tends to reduce the embodied and operational carbon emissions over a 30-year period (see figure 11). Overall, less aluminum mullion material is needed, which reduces the embodied carbon of the system. The demand for heating is lower due to less conductive heat loss through the aluminum frames. Fewer mullions means fewer glass edges, which leads to decreased air leakage through the facade, resulting in lower heating and cooling emissions.
- While the 1.52-meter (5 ft) module spacing may not be optimal, mullion spacing modules are typically in the 1.52- to 1.83-meter (5–6 ft) on-center range. These dimensions represent glazing unit sizes that are conventionally sized and relatively easy to source. The results show that increasing the width of that facade module could both improve thermal performance and embodied carbon—and therefore reduce building life-cycle carbon. However, larger glazing unit sizes may increase cost, make sourcing more challenging (since larger-than-standard units are made in a limited number of manufacturing facilities), and come with increased transportation costs and carbon emissions.
- Curtain wall frames and mullions contribute significantly to total 30-year carbon emissions. Reducing the impact of the frames by incorporating high-performance, thermally broken frames and, where practical, using structurally glazed silicone joints can reduce the amount of aluminum in a typical frame cross section. Use of facade components that are designed to be disassembled and recycled can also reduce the impact of the curtain wall frames. Fewer joints and breaks also reduce potential installation issues that cause air leakages over time.
- Figure 12 shows how the WWR, level of insulation in the spandrel panel, and glazing type affect total 30-year carbon emissions, maintaining a 1.52-meter (5 ft) curtain wall module. The results indicate that changing from double to triple glazing increases total carbon more than increasing the WWR from 50 percent to 65 percent. Increasing the spandrel panel insulation has a negligible impact on total carbon. These results are interesting, because common practice when increasing WWR is to change glazing type from double to triple glazing to minimize operational emissions. The results suggest this change in glazing could have the detrimental effect of increasing total carbon. When changing glazing type, therefore, it is important to consider the total life-cycle carbon impact of the decision and to choose glazing units with low embodied carbon emissions.

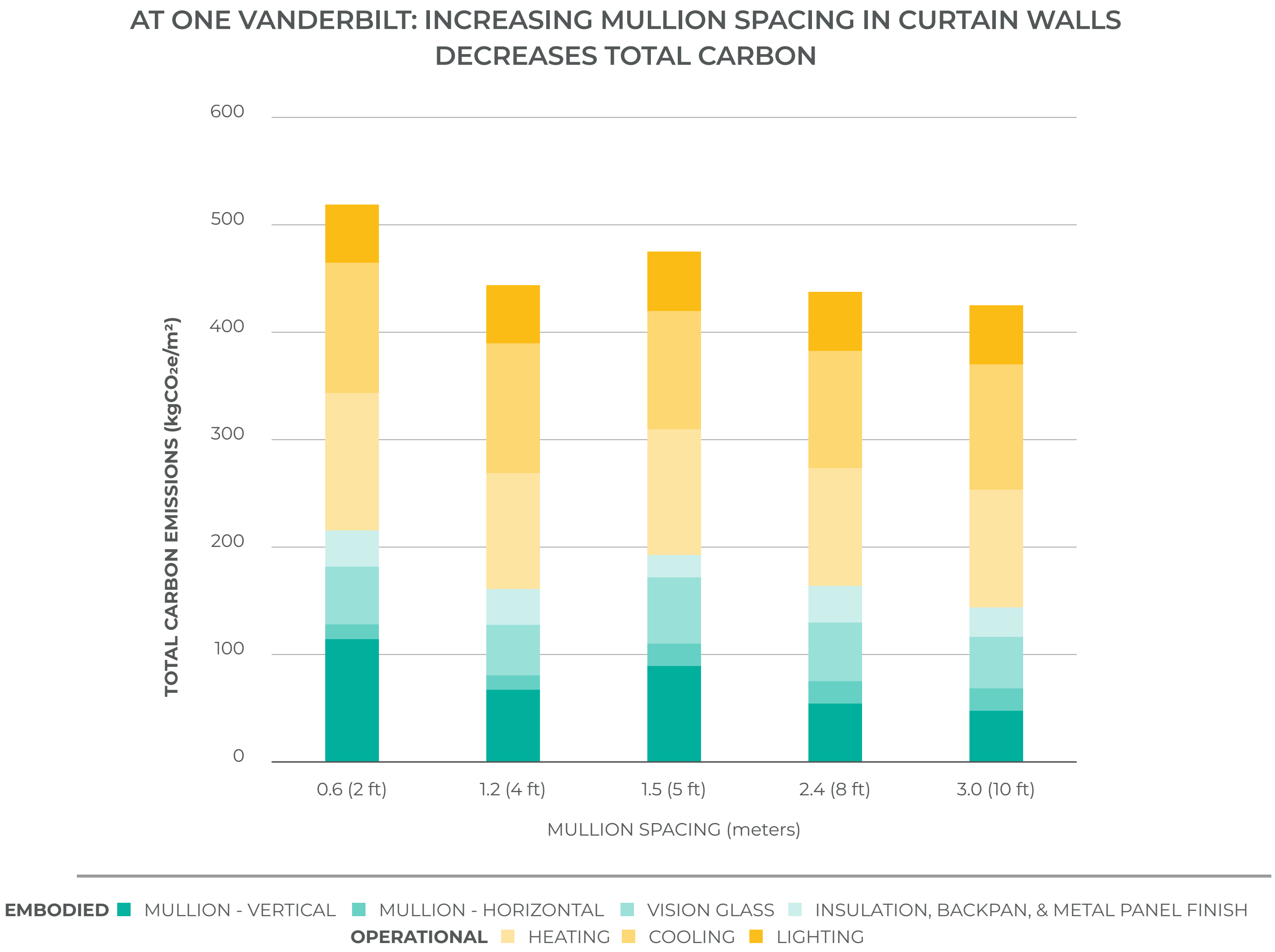


FIGURE 11. One Vanderbilt study results showing embodied and operational carbon emissions for a 30-year period, using varying mullion spacing (0.6, 1.2, 1.5, 2.4, and 3 meters or 2, 4, 5, 8, and 10 feet) and assuming double-pane glazing, one layer of spandrel insulation, 50 percent WWR, and an electricity grid that reduces emissions by 3 percent each year. Increasing curtain wall mullion spacing reduces the embodied emissions and decreases the operational emissions (due to lower infiltration and thermal bridging). Overall, the trend is lower total emissions from a spacing of 0.6 meters (2 ft) to 3 meters (10 ft), with best results at a 3-meter spacing.

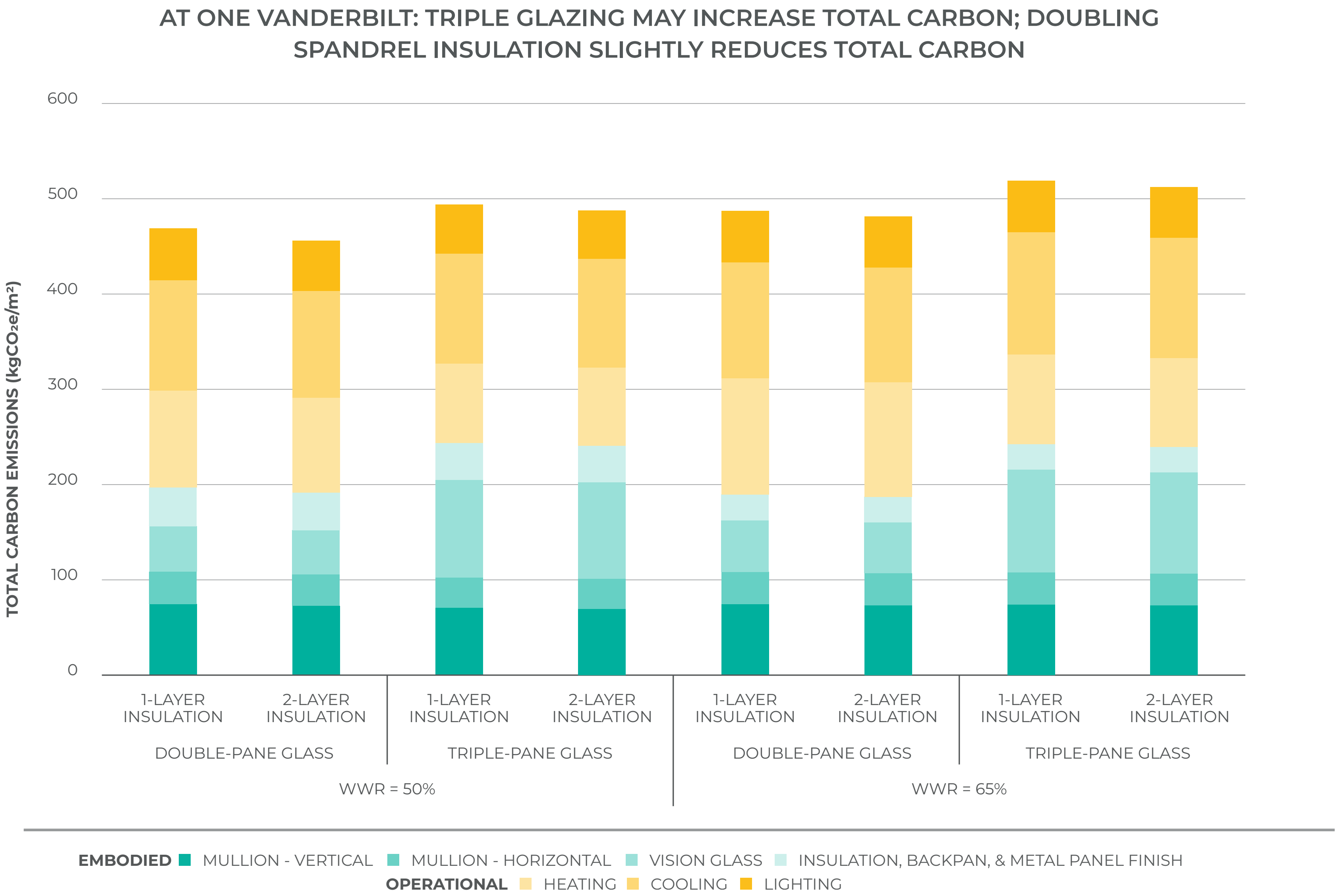


FIGURE 12. One Vanderbilt study results showing embodied and operational carbon emissions for a 30-year period, assuming an electricity grid that reduces emissions by 3 percent each year, showing all combinations of facade options by varying WWR, glazing type, and spandrel insulation amount. Mullion spacing is kept at 1.52 meters (5 ft). Besides mullion spacing increases, changing from double- to triple-pane glass is the most significant variable that increases total carbon emissions. Changing the level of insulation in the spandrel makes the least difference.

18 Robinson in Singapore uses shading to control interior comfort.

TIM GRIFFITH, COURTESY KPF

18 ROBINSON, SINGAPORE

IMPACTS OF SHADING DEVICES FOR HIGH-RISE OFFICE IN A TROPICAL CLIMATE

SUMMARY OF CASE STUDY

LOCATION: Singapore

BUILDING TYPE: High-rise, mixed-use office tower

CARBON CONTEXT: Singapore has announced net zero goals and implemented a carbon tax on emissions, and while the energy grid is more carbon-intense than London's and somewhat more so than New York's, it is on the lower end globally and getting cleaner, supporting a blend of embodied and operational carbon reduction measures.

CLIMATE CONTEXT: Tropical and getting hotter, with warm temperatures year-round and high humidity, requiring buildings to use significant cooling energy.

TRADEOFFS ANALYZED: Impacts of shading devices for windows (specifically, depth of shades and concrete versus aluminum for shade material) on reducing average and peak cooling energy needed.

TAKEAWAYS: In this context, shade devices of all depths and materials increase embodied carbon more than they save in reduced operational carbon; however, they reduce peak loads significantly, which allows for smaller and more efficient mechanical cooling systems and indirectly affects both operational and embodied carbon.

DESCRIPTION

The high-rise office tower at 18 Robinson is a 24,000-square-meter (259,400 sq ft) building that integrates the distinctive factors shaping the urban, environmental, and cultural backdrop of contemporary Singapore. The result is a distinctive and environmentally responsive building, offering both retail and office spaces designed to Green Mark Certification.[22] It has also been recognized with a 2019 Merit Award for Architecture and a Sustainable Future Award from the American Institute of Architects.

Situated at a V-shaped intersection, 18 Robinson effectively uses the site with a faceted tower. To satisfy Singapore's Landscape Replacement Area policy, a response to the island nation's limited available land area, 18 Robinson dedicates publicly accessible green spaces equivalent to the site area. These green areas include a landscaped podium and a Sky Garden on the rooftop, which incorporate trees, natural ventilation, and panoramic city views.

Urban-facing windows provide visibility into retail activities, and the podium's materials and faceted design connect it with the angular roof form and terra-cotta aesthetics of the well-known food market, Lau Pa Sat. Bob Graustein, KPF director, explains,

"The client was really keen on maximizing the views. So the views to the east would be to Singapore Marina Bay and the ocean beyond. The views to the South down Robinson Road would be very similar [in quality] to the views down Fifth Avenue in New York."

The tower's angled composition increases exposure to natural light while minimizing direct views into neighboring towers. The relatively small footprint of the site gave rise to an emphasis on facade performance for both sustainability and occupant comfort.

"With a small floor plate type building, the envelope matters more because more of the space is exposed to it." Graustein elaborates, "More of the experiential dimension of the building is mediated by the envelope versus a deep section building where you've got people further away from the facade."

TAKEAWAYS FOR DEVELOPERS

The 18 Robinson building provides an ideal context to evaluate the life-cycle carbon impacts of fixed shading devices in a warm equatorial context. Key findings include the following:

Exterior Shading Devices

- In Singapore, concrete and aluminum exterior shading devices typically emit more embodied carbon than they save in operational carbon.
- However, exterior shading plays an important role in reducing peak cooling loads in Singapore, with loads reduced as much as 38 percent. Reducing peak cooling can reduce the size of the mechanical system and its embodied carbon, save leasable space, and improve resilience of the local electricity grid.
- When designing a facade with exterior shading devices, sourcing low–embodied carbon materials can play a major role in minimizing total emissions.

CARBON CONTEXT

By 2020, Singapore had reduced emissions by 32 percent below business-as-usual levels; and between 2016 and 2021, it had reduced its electricity emissions from 0.424 $kgCO_2e/kWh$ to 0.406 $kgCO_2e/kWh$.[23, 24] Then, in 2022, Singapore announced a commitment to achieve net zero emissions by 2050. Critical to Singapore's national decarbonization strategy is the implementation of a carbon tax—the first of its kind in Southeast Asia. Its progressive adjustment of carbon emissions fees is intended to reinforce the price signal, motivating businesses and individuals to curtail their carbon footprint in adherence to national climate objectives.

The increased regulation of carbon emissions in Singapore is creating new business opportunities. Naree Phinyawatana, director at Atelier Ten's Southeast Asia office, is seeing increasing interest among its clients for carbon accounting in their corporate governance and a competitive business advantage from having technical capabilities in building decarbonization. "Our client often initiates the agenda," says Phinyawatana.

"They will ask, 'How are we doing on our overall carbon footprint?' or 'I'm interested in embodied carbon,' or 'I'm interested in carbon [in my building portfolio]. Can you tell me more about it?'"

Singapore's relatively high carbon emitting electrical grid will increase the relative impact of operational over embodied carbon and will favor design strategies that reduce operational carbon emissions.

CLIMATE ZONE CONTEXT

Singapore is located close to the equator, so it has a classic tropical climate with warm temperatures year-round. Temperatures rarely drop below 68 degrees Fahrenheit (20 degrees Celsius), even at night. The humidity levels are typically high, often exceeding 80 percent, contributing to perceived warmth and the need for extensive cooling and dehumidification. In warm climates such as this, shading devices have been used for centuries to maintain comfort and, more recently, to reduce energy consumption. In Singaporean office buildings, fixed shading elements can be made from lightweight, extruded aluminum components such as louvers, vertical fins, or mullion caps; by extending the concrete floor slab edge past the window; or through the use of attached precast-concrete shading elements. These elements improve operational carbon by reducing the energy needed for cooling, but they increase the facade's embodied carbon.

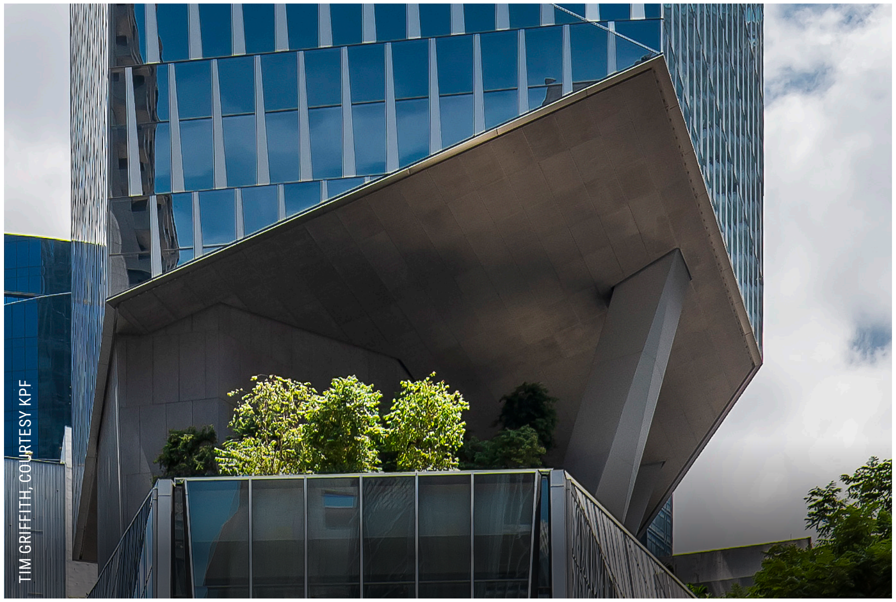
Singapore's building codes require that buildings meet facade shading performance targets through a combination of external shading devices and low solar heat gain coefficient (SHGC) glass.[25] Cerezo Davila explains,

"Singapore's codes and Green Mark certification system have been able to develop a locally specific, increasingly restrictive solar control thermal calculation that drives a lot of current envelope design in the country. In our projects, we work backwards from that target to determine how much glazing you can have, and you either compensate with shading or you compensate with less glass."

Buildings which aim for larger glass areas often compensate by adding fixed shading elements with increasing depths or projection factors.

As a small island country with limited local manufacturing, sourcing unique glazing technology can be challenging in Singapore. This is especially the case with high-performance glazing systems. Joelle Chen, the head of sustainability at Lendlease APAC, recounts hearing of a (non-Lendlease) project that

"used glass from China that was fritted in Europe before landing in Singapore . . . the amount of savings that one may get operationally may not be worth the embodied energy that's in the manufacturing and transportation process. It's crucial to consider embodied carbon in its own right, and procure the lowest-carbon materials technically and commercially feasible at this current point in time."


TIM GRIFFITH, COURTESY KPF

ANALYSIS: SHADING ELEMENTS TRADEOFFS

In commercial office buildings, shading elements address a number of intersecting building performance goals. According to KPF's Cerezo Davila, in a building with a small floor plate,

"The first bay of office workstations [at the perimeter] ends up accounting for maybe 40 percent of the occupied area, as opposed to an office building with a deeper floor plate. So the facade determines much, much more of the cooling loads in a building like 18 Robinson."

If designed appropriately, facades can allow for increased glass area without incurring additional cooling energy costs. This improves daylight and views, both of which increase asset value and have been shown to improve productivity, user satisfaction, and well-being. Shading devices can also reduce peak cooling loads, which can enable smaller mechanical systems that consume less building area and are less expensive. This is especially true of buildings with narrow footprints.

The ripple effects from decreased cooling requirements can affect everything from indoor comfort to duct sizing, floor-to-floor height, facade area, and the overall size of mechanical systems. When taken in aggregate, the impacts of shading systems as part of an integrated design process can reduce building costs, reprioritize investments toward tangible benefits for building owners and users, and reduce the overall embodied carbon investment.

The 18 Robinson building was used to study the impact of shading depth and shading material on total carbon emissions. The specific facade variables that were evaluated are shown in figure 13.

18 ROBINSON

18 Robinson in Singapore was used as the context to study the life-cycle carbon impact of 14 different configurations of facade shading depth and materials.

x14 options

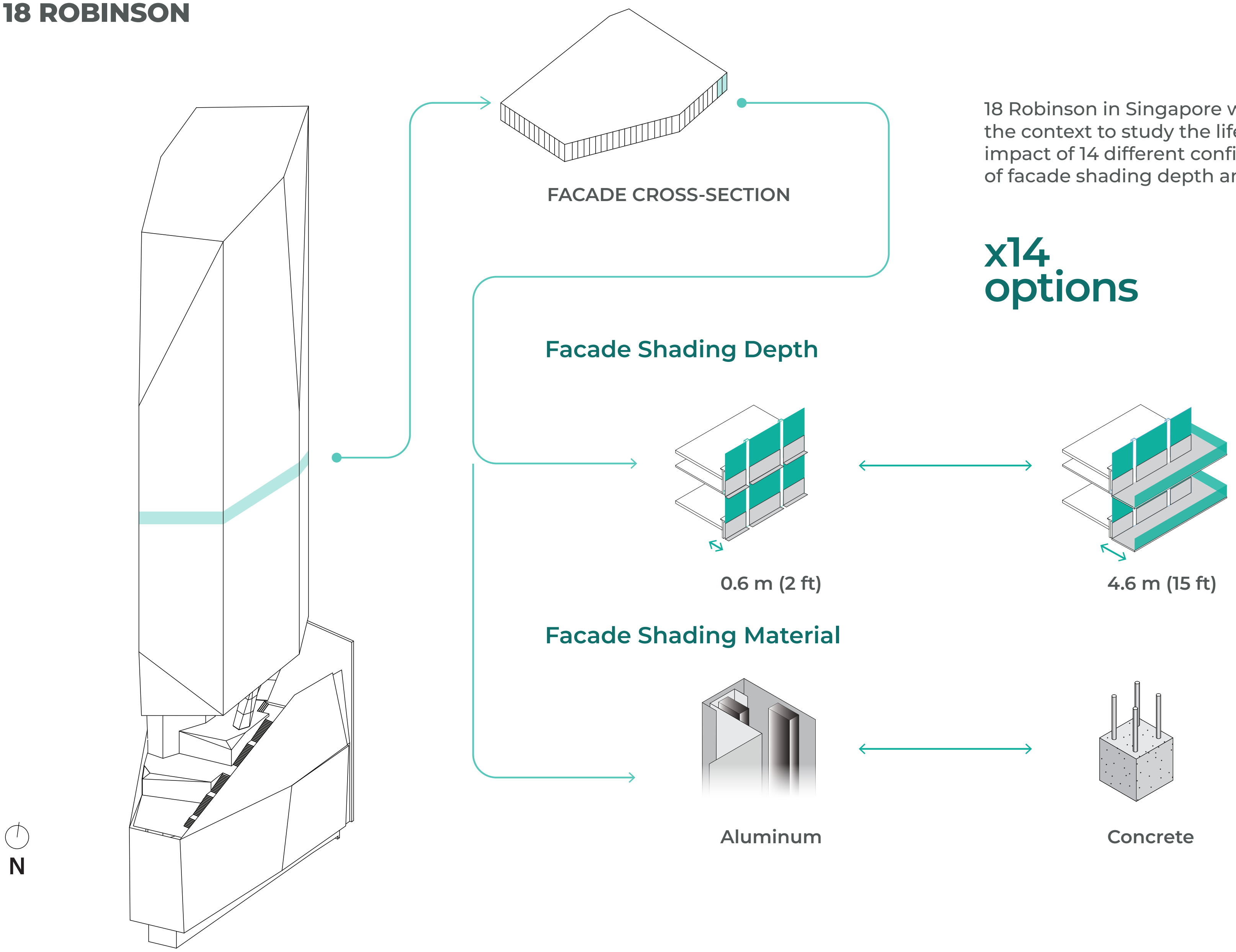


FIGURE 13. Diagram of the two facade parameters studied at 18 Robinson: (1) shading depth and (2) shading material.

THE SWEET SPOT FOR 18 ROBINSON: OPTIMIZING SHADING DEVICES

The results of the 30-year total carbon analysis for 18 Robinson can be summarized as follows:

- In Singapore, which has a hot, humid, and overcast climate, the percentage of an office building cooling load driven by solar gain is outweighed by other sources of heat, such as equipment, ventilation air, and dehumidification (see figure 14). The analysis did not see sufficient operational carbon emissions reductions over 30 years to warrant the inclusion of large shading devices of significant depth (see figures 15 and 16).
- Nevertheless, in this analysis, concrete projections (such as balconies) clearly outperform aluminum in terms of embodied carbon emissions, with material quantities in shading design varying dramatically based on thickness, product-type (e.g., light gauge external venetian blinds versus custom fabricated aluminum louver assemblies), or recyclability. However, for a number of reasons, a simple life-cycle carbon analysis is insufficient to determine the carbon return on investment on shading elements. For example, shading elements can be composed of concrete floor slab projections, which offer increased leasable or usable areas as balconies. Shading elements also have a significant impact on the visual and thermal experience of spaces (as shown in figure 17), which indicates differences in solar heat effects at the perimeter for north-, south-, east-, and west-facing spaces.


TIM GRIFFITH, COURTESY KPF

- As indicated in figures 15 and 16, embodied carbon investments in fixed exterior shading may not show dramatic changes in building energy use and thus a simple view of this tradeoff could conclude that additional shading is either a “wash” or even a slight net negative in terms of life-cycle carbon.
- However, peak load reductions, through integrated design, offer substantial opportunities for embodied carbon reductions. As described above, peak loads typically establish building mechanical system sizes, which in turn drive duct sizes. In many buildings, duct sizes determine floor-to-floor heights, which in turn set the amount of facade area, the structure sizing, and even the number of floors allowable and leasable area. These effects can increase leasable area and building asset value appreciably—especially in high-rise construction. Peak loads also determine the amount of mechanical equipment needed to maintain comfort capacity.
- Shading can reduce peak loads (see figure 17) by as much as 50 percent and can reduce the amount of cost and embodied carbon associated with installed HVAC cooling equipment by similar percentages. Each of these impacts of shading can reduce both substantial embodied and operational carbon over the service life of a building.

FIGURE 14. Annual heat gains in a typical Singapore office building. Because direct solar gain is not the main driver of heat gains throughout the year in any building orientation, shading devices offer limited operational emissions benefits in Singaporean buildings.

AT 18 ROBINSON: ADDING ALUMINUM SHADES SIGNIFICANTLY INCREASES TOTAL CARBON

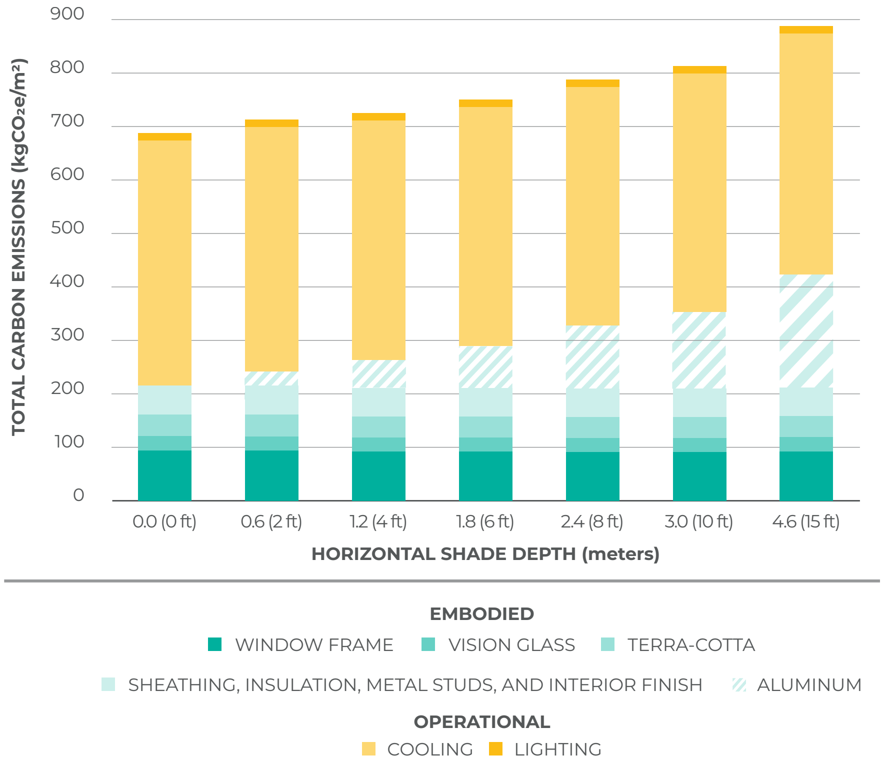


FIGURE 15. Study results showing embodied and operational GWP emissions for a 30-year period for a Singapore office building with an aluminum shade and varying horizontal aluminum shade depth, assuming an electricity grid that reduces emissions 3 percent each year. Increasing the shade depth significantly increases the total emissions, because the reductions in operational carbon from mechanical cooling are significantly outweighed by the increase in embodied carbon from the shades.

AT 18 ROBINSON: ADDING CONCRETE SHADES MODESTLY INCREASES TOTAL CARBON BUT REDUCES PEAK LOADS

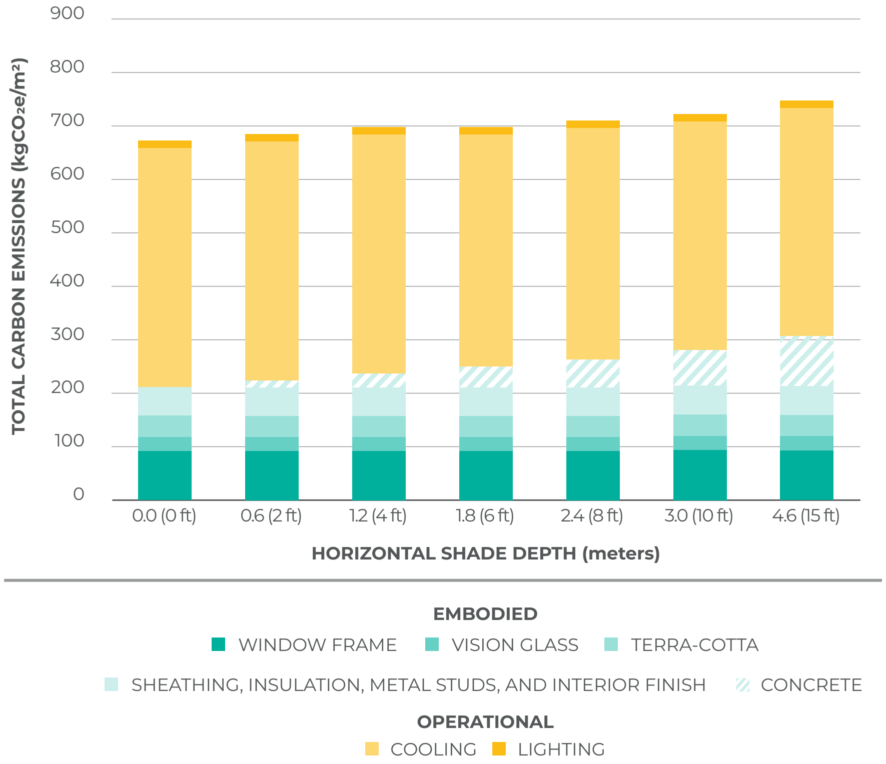


FIGURE 16. Study results showing embodied and operational GWP emissions for a 30-year period for a Singapore office building with a concrete shade and varying horizontal concrete shade depth, assuming an electricity grid that reduces emissions by 3 percent each year. Increasing the shade depth increases total emissions but not as much as with an aluminum shade, due to the lower embodied carbon of the concrete shade. This result underscores the importance of considering low-carbon materials in exterior shading design. In this instance, the main advantage of the exterior shades is in reducing peak load, not in reducing total carbon emissions.

AT 18 ROBINSON: EXTERIOR SHADES SUBSTANTIALLY REDUCE PEAK LOADS

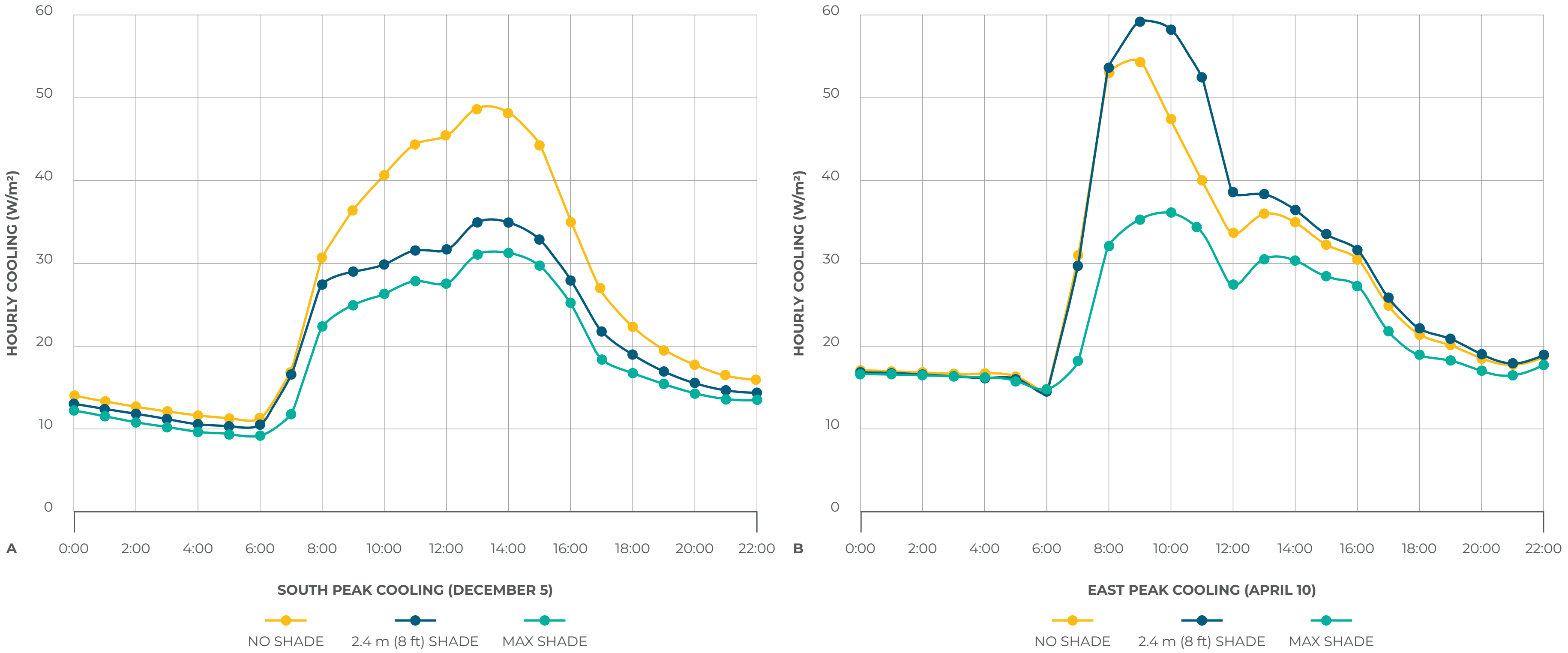


FIGURE 17. Hourly cooling loads during peak cooling days per orientation for a typical Singapore office high-rise with three solar shading scenarios: (1) no shading, (2) 2.4-meter (8 ft) shade, (3) maximum possible reduction in peak cooling with exterior shading. A 2.4-meter (8 ft) exterior shading device can significantly reduce peak cooling loads on a south facade (north facade is similar due to solar geometry in Singapore). On the east (and west) facade, however, a 2.4-meter (8 ft) shade is not as effective at reducing peak cooling loads, due to low-angle sunlight that is not easily blocked by horizontal shading devices.

CONCLUSION

The process of designing building facades involves balancing multiple objectives. These objectives range from qualitative aims such as preserving views, enhancing thermal comfort, and maximizing daylight to quantifiable factors such as cost, construction schedules, and effects on HVAC systems. Reducing carbon emissions from materials and operations is increasingly recognized as another design goal, largely driven by a desire to reduce the environmental impacts of buildings by building professionals, owners, legislators, and society as a whole.

Until recently, life-cycle carbon emissions were difficult to quantify. Now that they are quantifiable, they can be considered as a factor among the many other goals that a building must meet.

Often, tradeoffs occur between embodied and operational carbon emissions: changing the materials of the facade to reduce operational carbon emissions can lead to increases in embodied emissions. This report lays out a method for finding the carbon sweet spot—the facade design that optimizes investments in embodied and operational carbon emissions to achieve the minimum total emissions—and offers three illustrative case studies for doing so. The analyses yielded several high-level takeaways:

Carbon analyses can consider both embodied and operational carbon for maximum impact. Currently, energy performance and material selection are often considered independently. Finding the carbon sweet spot requires assessing embodied carbon emissions from materials and operational emissions together. New tools, data availability, and methods such as whole building life-cycle assessment enable designers to maximize building value while minimizing life-cycle carbon emissions. Understanding embodied and operational carbon tradeoffs can improve building performance and deliver the best value-to-cost ratio.

The amount of glazing on a building's facade significantly influences both embodied and operational carbon emissions. In terms of embodied carbon, glazed sections generally have higher carbon intensity compared with nonglazed parts of the facade. Regarding operational carbon, designs featuring larger glazed sections experience greater heat transfer through the facade, necessitating more energy for heating or cooling. Strategically planning the placement of glazing areas to minimize their extent and optimize design for low carbon emissions is crucial.

Triple glazing should be carefully assessed. Triple glazing can effectively reduce heating energy consumption, thus decreasing operational carbon emissions. However, it may result in higher embodied carbon emissions compared with double glazing. When opting for triple glazing, selecting units with low embodied carbon is crucial to mitigate the overall emissions impact.

Increasing wall insulation tends to make only a modest difference in total carbon emissions when starting with standard code minimums. Increasing wall insulation tends to reduce the need for mechanical heating, thus lowering operational emissions. Embodied emissions, however, increase with more insulation to the point of negating the savings in operational emissions, depending on the insulation type and sourcing.

Smaller curtain wall module widths can increase total carbon emissions. Aluminum frames that make up standard curtain wall systems are carbon intensive. Smaller curtain wall modules tend to have more curtain wall framing material, significantly increasing embodied carbon. Operational carbon also increases with smaller wall modules, due to thermal bridging and air infiltration. When designing a curtain wall system for low total carbon emissions, the curtain wall module is an important variable to assess.

Shading devices may increase total carbon emissions, but significantly reduce peak loads. Exterior shading devices can be effective in lowering cooling energy use in hot climates. However, the savings in cooling energy and thus operational carbon emissions may be outweighed by the embodied carbon of the shading material. When using exterior shading, the shading can be strategically designed to optimize reductions in operational emissions while using less material. The design can also consider shading material that has a low embodied carbon to minimize total carbon emissions.

Understanding the impact of local fuel sources and decarbonization policy is key to navigating carbon tradeoffs. The carbon intensity of electricity varies widely depending on generation sources and regional and international availability of energy sources. Similarly, building owners can consider the carbon impacts of continuing to incorporate fossil fuels in their buildings. In addition, an analysis of life-cycle carbon emissions should incorporate likely scenarios for the decarbonization of the electrical grid over time driven by policy, economic factors, and technological changes. This trajectory can significantly influence operational carbon emissions over a building's service life and affect how much a developer may want to invest in added materials and some increases in embodied carbon to achieve operational savings.

Finally, embodied and operational carbon tradeoffs are not only for new construction. The most carbon efficient building may be one that already exists. Extending the life of a building and its structure can preserve neighborhood heritage and avoid substantial embodied carbon emissions. Facade improvements in existing buildings can leverage previous generations' investments while creating buildings that meet the operational performance objectives for a low-carbon future. Looking forward, Duncan Cox, director at Thornton Tomasetti explains,

"Now we're looking at: What do we do with these 1970s, 80s, 90s–era building facades? [We are] talking to the facade contractors about what we can and can't do, and they are coming around to the idea of retrofitting some of these facades and adapting them for the future."

Ultimately, reducing the carbon impact of materials by building for longevity, choosing recyclable materials, and considering building reuse can make the most of a material's operational carbon savings. A building that is flexible to future uses and built to last will make the most of the embodied carbon spent to built it by increasing life-cycle value.

"Durable buildings with thoughtful design that will stand the test of time are going to make one of the biggest differences in environmental impact long term, because people will want to be there. And if buildings are flexible, they can accommodate future operational requirements, whether it's for engineering and energy efficiency or for changes in occupancy or market demand. I think that's the most critical thing that we could be doing as an industry,"

offers Caroline Johns with Pembroke Real Estate.

ACKNOWLEDGMENTS

The Urban Land Institute would like to thank KPF for providing the endowment and fellowship that supported this work in memory of A. Eugene Kohn, co-founder of KPF and the first architect Life Trustee of ULI. ULI thanks the following industry leaders and stakeholders for providing their time and expertise for this research. Affiliations were correct at time of publication.

Andrew Bush
Principal
Morgan Creek Ventures

Carlos Cerezo Davila
Environmental Design Director
KPF

Caroline Johns
Director, Sustainability
Pembroke

Charles Olson
Senior Associate Principal
KPF

Duncan Cox
Sustainability Associate Director
Thornton Tomasetti

Ethan Tucker
Sustainability Communications Coordinator
KPF

Joelle Chen
Head of Sustainability, Asia
Lendlease

Laura Vulaj
Senior Vice President, Hospitality & Sustainability
SL Green

Maurya McClintock
Director
McClintock Facade Consulting

Michael Long
Group Head of Sustainability
New World Development

Naree Phinyawatana
Director (Asia)
Atelier Ten

Nicole McGlinn-Morrison
Director
KPF

Robert Graustein
Director
KPF

REPORT TEAM

Lead Authors

Christopher Meek
Professor of Architecture, University of Washington; Director, Integrated Design Lab

Tomás Méndez Echenagucia
Assistant Professor of Architecture, University of Washington

Teresa Moroseos
Post-Doctoral Scholar, Integrated Design Lab, University of Washington

Project Staff

Billy Grayson
Executive Vice President, Centers and Initiatives

Marta Schantz
Co-Executive Director, Randall Lewis Center for Sustainability in Real Estate

August Williams-Eynon
Manager, Randall Lewis Center for Sustainability in Real Estate

Libby Riker
Senior Editor

Karen Coda, Publications Professionals LLC
Manuscript Editor

Brandon Weil
Art Director

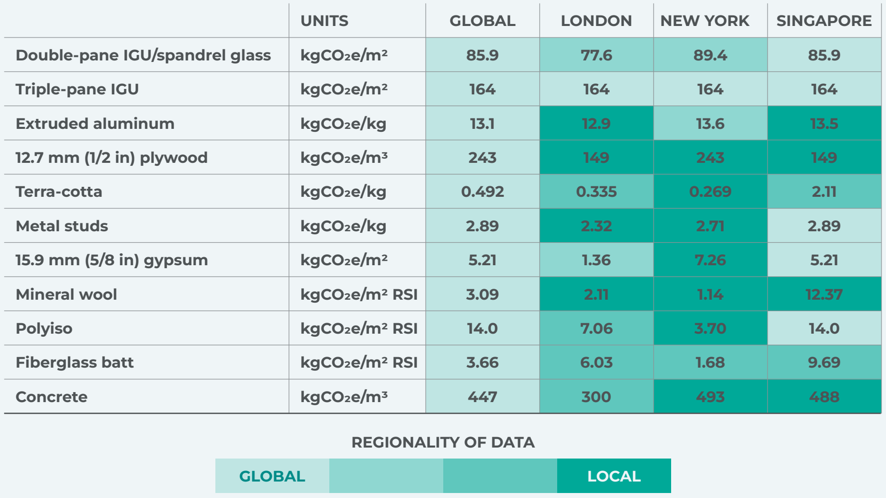
Thomas Cameron
Graphic Designer

Nicole Long
Traffic Manager

Timothy Koehler
Director, Creative Services

Craig Chapman
Senior Director, Publishing Operations

APPENDIX: WBLCA TOOLS AND METHODS



	UNITS	GLOBAL	LONDON	NEW YORK	SINGAPORE
Double-pane IGU/spandrel glass	kgCO$_2$e/m^2	85.9	77.6	89.4	85.9
Triple-pane IGU	kgCO$_2$e/m^2	164	164	164	164
Extruded aluminum	kgCO$_2$e/kg	13.1	12.9	13.6	13.5
12.7 mm (1/2 in) plywood	kgCO$_2$e/m^3	243	149	243	149
Terra-cotta	kgCO$_2$e/kg	0.492	0.335	0.269	2.11
Metal studs	kgCO$_2$e/kg	2.89	2.32	2.71	2.89
15.9 mm (5/8 in) gypsum	kgCO$_2$e/m^2	5.21	1.36	7.26	5.21
Mineral wool	kgCO$_2$e/m^2 RSI	3.09	2.11	1.14	12.37
Polyiso	kgCO$_2$e/m^2 RSI	14.0	7.06	3.70	14.0
Fiberglass batt	kgCO$_2$e/m^2 RSI	3.66	6.03	1.68	9.69
Concrete	kgCO$_2$e/m^3	447	300	493	488

FIGURE A-1. A1–A3 emissions for different materials for London, New York, and Singapore used to calculate "embodied" emissions in the case study results (data accessed are "conservative" values from EC3 database, except for triple-pane IGU where "average" values were used due to low availability of data, January 2024).

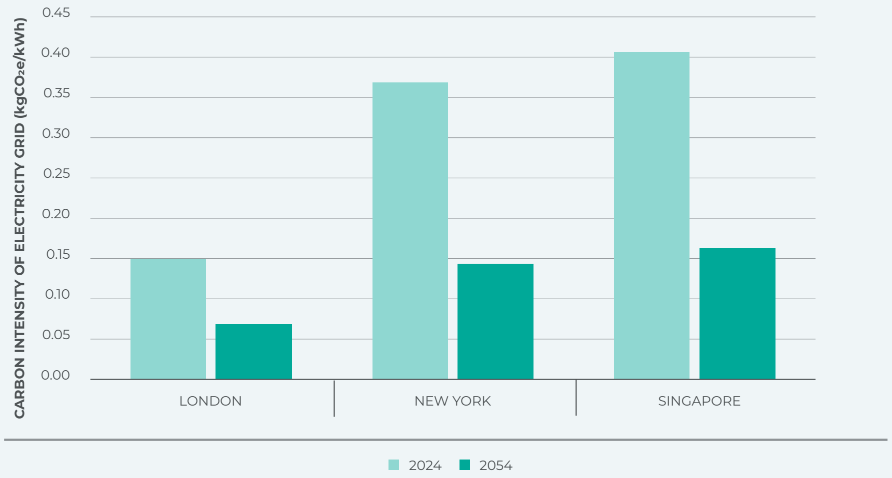


FIGURE A-2. The carbon intensity of electricity generation used for the three study locations for two different time points: (1) current emissions in 2024, and (2) emissions in 2054 assuming the electricity grid decarbonizes by 3 percent each year.

MULLION SPAN (m)	KAWNEER MODEL	DEPTH (mm)	WIDTH (mm)	HORIZONTAL SECTION (mm^2)	VERTICAL SECTION (mm^2)
0.6	162001 - heavy	152	63.5	1,523	1,819
1.2	162003 - heavy	191	63.5	1,723	1,923
1.5	162064	267	63.5	2,839	3,052
2.4	162064	267	63.5	2,839	3,052
3.0	162064	267	63.5	2,839	3,052

FIGURE A-3. Depth, width, horizontal area, and vertical area of aluminum in curtain wall per mullion span, based on the Kawneer 1600 Wall System Curtain Wall. These numbers were used to quantify the volume of aluminum in the horizontal and vertical mullions in this report.

NOTES

INTRODUCTION

[1] Carbon emissions serve as the primary metric for evaluating the environmental impact of buildings. Carbon emissions are measured in global warming potential (GWP), which represents the relative contribution of greenhouse gasses to global warming over a specified period compared with CO_2. The unit for quantifying GWP in this report is kilograms of CO_2 equivalent ($kgCO_2e$).

THE BUSINESS CASE FOR LOW-CARBON BUILDINGS

[2] Urban Land Institute, *Embodied Carbon in Building Materials for Real Estate* (Washington, DC: Urban Land Institute, 2019), https://americas.uli.org/wp-content/uploads/ULI-Documents/Greenprint-Embodied-Carbon-Report_FINAL.pdf.

[3] Urban Land Institute, *The Materials Movement: Creating Value with Better Building Materials* (Washington, DC: Urban Land Institute, 2024), https://knowledge.uli.org/reports/research-reports/2023/the-materials-movement-creating-value-with-better-building-materials.

Investor and Tenant Demand

[4] For more information on science-based targets, see https://sciencebasedtargets.org/.

Policy Compliance

[5] See NYC Sustainable Buildings, Local Law 97, https://www.nyc.gov/site/sustainablebuildings/ll97/local-law-97.page.

[6] See "Embodied Carbon Policy Tracking Map," https://batchgeo.com/map/0a7f165939da9d291b183cfc7c326726.

Lower Operating Cost

[7] For more information about the firm, see https://www.morgancreekventures.com/.

DESIGNING FOR EMBODIED AND OPERATIONAL CARBON

Sources of Carbon Emissions within Buildings: Why Focus on Facades?

[8] Current research shows that HVAC systems can also be significant drivers of carbon emissions over the lifespan of the building, particularly when considering fugitive refrigerant emissions.

[9] Mendez Echenagucia, Tomas, Teresa Moroseos, and Christopher Meek, "On the Tradeoffs between Embodied and Operational Carbon in Building Envelope Design: The Impact of Local Climates and Energy Grids," *Energy & Buildings* 278 (2023).

CASE STUDIES: FINDING THE CARBON SWEET SPOT

How the Carbon Sweet Spot Was Evaluated

[10] The results in this report only include product stage (A1–A3) emissions and operational energy (B6) emissions. Construction stage (A4–A5) emissions were excluded because they are relatively small. Use stage (B1–B7) emissions were excluded because maintenance, repair, and replacement are negligible in the time frame analyzed (30 years). End-of-life stage (C1–C4) emissions were excluded because of significant uncertainty about these emissions and because they are not relevant to the design decisions discussed in this report.

[11] To learn more about defining the object of study in a WBLCA, see https://carbonleadershipforum.org/wp-content/uploads/2019/05/CLF-LCA-Practice-Guide_2019-05-23.pdf.

[12] Kawneer was used as the basis of design for the curtain wall and punch window systems to estimate amount of aluminum in mullion profiles. Appropriate Kawneer curtain wall models per span were chosen to resist wind loads per this manual: Kawneer Company Inc., "1600 Wall System 1 Curtain Wall," EC 97911-304, January 2024, https://www.kawneer.us/kawneer_files/shared%20files/97911-Arch_Manual/ADMD010EN.pdf.

[13] Access the EC3 tool at the Building Transparency website: https://www.buildingtransparency.org/.

Uncertainties in This Analysis (sidebar)

[14] Jie Li et al., "Identifying Uncertainties in the Whole Life Carbon Assessment of Buildings: Sources, Types, and Potential Actions." *Building and Environment* 244 (2023): 110779, https://doi.org/10.1016/j.buildenv.2023.110779.

[15] Angelica Mendoza Beltran et al., "Quantified Uncertainties in Comparative Life Cycle Assessment: What Can Be Concluded?," *Environmental Science & Technology* 52, no. 4 (2018): 2152–61, https://doi.org/10.1021/acs.est.7b06365; Joshua L. Sohn et al., "Life-Cycle Based Dynamic Assessment of Mineral Wool Insulation in a Danish Residential Building Application," *Journal of Cleaner Production* 142 (2017): 3243–53, https://doi.org/10.1016/j.jclepro.2016.10.145; Elorri Igos et al., "How to Treat Uncertainties in Life Cycle Assessment Studies?," *The International Journal of Life Cycle Assessment* 24, no. 4 (2019): 794–807, https://doi.org/10.1007/s11367-018-1477-1.

One Crown Place, London: Impacts of Glass Area and Wall and Window Performance in a Low-Carbon Grid

[16] Mayor of London, *London Net Zero 2030: An Updated Pathway* (London: Greater London Authority, 2022) https://www.london.gov.uk/sites/default/files/london_net_zero_2030_-_an_updated_pathway_-_gla_response_1.pdf.

[17] National Grid ESO, "Carbon Intensity API," https://carbonintensity.org.uk.

One Vanderbilt, New York City: High-Rise Office Unitized Curtain Wall in a Temperate Climate

[18] Center for Climate and Energy Solutions, "Decarbonizing U.S. Power," 2018, https://www.c2es.org/document/decarbonizing-u-s-power/.

[19] For 2022 emissions data, see U.S. Environmental Protection Agency, "Emissions & Generation Resource Integrated Database (eGRID), www.epa.gov/egrid.

[20] NYC Mayor's Office of Climate and Environmental Justice, "Systems: Building a Clean, Resilient, and Affordable Energy System," https://climate.cityofnewyork.us/subtopics/systems/. 2021 NYCW eGRID subregion output emission rates were used for New York City's electrical grid emission factors, available on the EPA's website: https://www.epa.gov/egrid/historical-egrid-data.

[21] See New York State, "Climate Act," https://climate.ny.gov/.

18 Robinson, Singapore: Impacts of Shading Devices for High-Rise Office in a Tropical Climate

[22] Singapore Building and Construction Authority, "Green Mark Certification Scheme," https://www1.bca.gov.sg/buildsg/sustainability/green-mark-certification-scheme.

[23] National Climate Change Secretariat, "Singapore and International Efforts," https://www.nccs.gov.sg/singapores-climate-action/singapore-and-international-efforts/.

[24] National Climate Change Secretariat, "Power," https://www.nccs.gov.sg/singapores-climate-action/mitigation-efforts/power/.

[25] When 18 Robinson was originally designed, it included glass with a 0.287 SHGC. Today a similar building facade would be required to use glazing in the 0.20–0.22 SHGC range to meet newer Singapore energy codes. The analysis we present uses the more stringent glazing properties for its basis of evaluation.