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Abstract

Some 97 cities worldwide, including most of the world's megacities with a population of 10 million or more, have signed onto the C40 Cities Climate Pledge goal of achieving net-zero carbon emissions by 2030. As this date edges closer, this paper steps back to assess some of the best-in-class tall buildings that stand as exemplars, representing the progress that has been made, as well as the challenges that still lie before us. Recognizing that the building industry itself will be a critical component, while certainly not the only factor, in cities realizing these goals, it is incumbent upon the developers, designers, and constructors of tall buildings to comprehend what is possible, and advocate for the best practices represented by these projects, both within their industry and in the communities where they build.

Keywords: Carbon Emissions, Embodied Energy, Net-Zero, Operational Energy

Introduction

The Intergovernmental Panel on Climate Change (IPCC) is the United Nations (UN) body responsible for assessing data and science relating to climate change. In 2015, at the UN Framework Convention on Climate Change (UNFCCC), the IPCC was tasked with examining the impact of global warming and the pathways to reduce greenhouse gas (GHG) emissions. In 2018, the IPCC Special Report: Global Warming of 1.5°C was published, which presented a blunt outlook for the future: "Without increased and urgent mitigation ambition in the coming years, leading to a sharp decline in greenhouse gas emissions by 2030, global warming will surpass [an average increase in temperatures of 1.5 degrees Celsius (°C) above pre-industrial levels] in the following decades, leading to irreversible loss of the most fragile ecosystems, and crisis after crisis for the most vulnerable people and societies" (IPCC 2018).

While an increase in 1.5°C may not seem significant, if overall global warming reaches 2.0°C the world will be confronted with considerably more stark results. In a climate risk assessment, the IPCC indicates that global food security, water resources, and exposure to drought, heat, and coastal submergence transition from "moderate" to "high" risk when temperatures rise between 1.5°C and 2.0°C on average (IPCC 2018). This research reinforced the goals of the UN Paris Agreement of 2015, which is a legally-binding, international treaty for participating nations to limit global warming to well below 2.0°C, and preferably to 1.5°C, compared to pre-industrial levels (UN 2015). With increasing populations, in order to avoid surpassing the 1.5°C, significant innovations and improvements must be made to limit greenhouse gas emissions.

As part of this agreement, countries must transparently report all climate change mitigation efforts and progress in achieving the same. This has seen efforts from international Green Building Councils (GBCs) to create strategies to reduce emissions released from the building industry, with the eventual goal to have all new construction be net-zero. In other words, for any quantity of greenhouse gas emissions released into the atmosphere by the construction or operation of a building, the equivalent amount is also removed as an outcome of its design.

The Impact of Tall Buildings

According to the UN Environmental Committee, "the buildings and construction sector should be a primary target for GHG emissions mitigation efforts."

Although buildings showed progress between 2013 and 2016, when emissions began leveling off, in 2018, the total gigatons of carbon dioxide ($GtCO_2$) increased 2 percent for the second consecutive year, reaching 9.7 $GtCO_2$ (GlobalABC and IEA 2019). In order to meet the requirements of the Paris Agreement and avoid the climate, economic, and social consequences of a 2.0°C increase in global warming, all building emissions must be reduced, which is directly at odds with the fact that the world's total built floor area and the human population have been consistently increasing over the past decade (See *Tall Buildings in Numbers*, page 50).

The building industry accounts for approximately 39 percent of the world's energy- and process-related carbon dioxide emissions. While 28 percent of these emissions derive from the operation of existing buildings (17 percent for residential buildings and 11 percent for other functions), 11 percent of all emissions resulted from the construction industry and manufacturing of building construction materials and products, such as steel, cement, and glass (GlobalABC and IEA 2019). The emissions from these two categories are typically referred to as a building's "operational carbon," or the amount of emissions derived from a building while it is in-use; and secondly, a building's "embodied carbon," or the amount of emissions from the extraction, manufacturing, transportation, construction, and eventual demolition/disposal of the materials to make a building (SPOT UL 2020). Most of the operational emissions, or approximately 19 percent of all CO_2 emissions, were indirect, or energy that is generated off-site to power the buildings. Some nine percent was from direct, operational emissions, such as when there is on-site combustion of fossil fuels for heating and cooling.

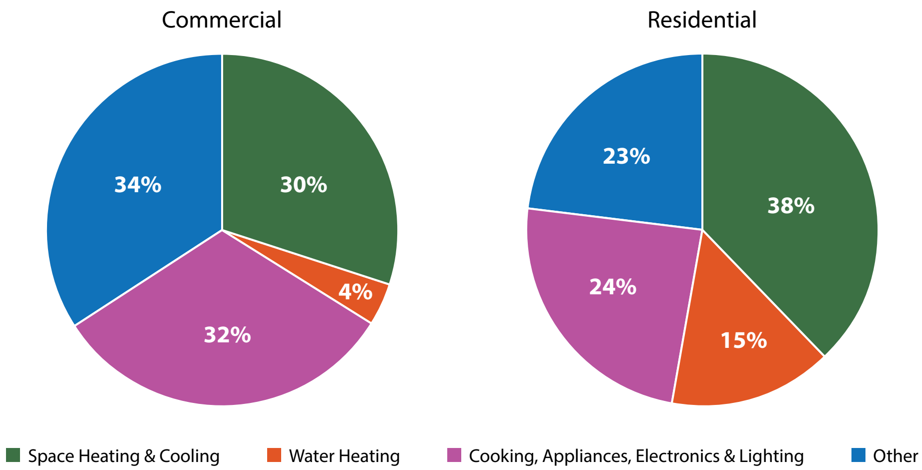

Figure 1. In US buildings, the biggest contributors to CO_2 emissions are space heating and cooling, water heating, cooking, appliances, electronics, and lighting. "Other" refers to items classified as "miscellaneous electric loads" by the US Energy Information Administration, such as data servers, ceiling fans, and pool pumps.
Source: US Energy Information Administration, 2018.

> "It is an unfortunate irony that many technologies employed to reduce operational emissions can actually increase embodied energy use."

Operational and Embodied Energy Goals

The International Energy Agency (IEA) indicates that limiting the increase in average global temperatures to 1.5°C requires reducing global CO_2 emissions to net zero by 2050, which "calls for nothing less than a complete transformation of how we produce, transport and consume energy." It is predicted that total CO_2 emissions from the building sector will need to decline more than 95 percent by 2050, while in this same time period, the building sector is expected to increase by 75 percent in terms of overall floor area with much of the growth concentrated in emerging markets and developing economies (IEA 2021). Technologies that are widely already available on the market, such as improved envelopes for new and existing buildings, heat pumps, and energy-efficient appliances, are expected to help achieve this transformation. In US buildings, the biggest contributors to emissions are space heating and cooling, water heating, cooking, appliances, electronics, and lighting (see Figure 1) (US Energy Information Administration 2018). To accelerate the impact that the building industry can have towards a net-zero future, organizations such as the World Green Building Council (WorldGBC) launched the "Net-Zero Carbon Buildings Commitment," which focuses on combating the most impactful aspects of building emissions and promoting net-zero operational carbon as a goal for all buildings and cities.

These strategies, roadmaps, policies and commitments, while aspirational, set out a guide to motivate the building industry to achieve a net-zero future for operational carbon, one of the single largest contributors to CO_2 emissions. With that said, as operational carbon is reduced, the impact of embodied carbon will grow in importance, and it is an unfortunate irony that many of the technologies employed to reduce operational emissions can actually increase embodied energy use. Before 2050, embodied carbon is expected to account for

Figure 2. One Central Park, Sydney, is distinguished by its 5-kilometer-long system of hydroponic planters and 40 cantilevered heliostats that track the sun to optimally direct solar rays toward underheated and underlit areas. © Marshall Gerometta

Figure 3. The heliostats on One Central Park, Sydney, provide hours of sunlight and heating to areas normally shaded. © Terri Meyer Boake

half of the building sector's total carbon footprint (WorldGBC 2019). As changes and improvements are made to operational carbon emissions, there should be a consideration of the embodied energy being consumed, in order to ensure that resources are used efficiently.

Addressing Emissions in Tall Buildings

Globally, buildings have already started to embrace sustainability as a primary driver of their design. This section will take an informal look at a number of tall buildings globally, one in each region, that embraced the local environment and deployed design measures to reduce both operational and embodied emissions. To learn about other measures to reduce operational and embodied emissions, and more buildings that embrace sustainable technologies, visit the accompanying *Tall Buildings in Numbers* Data Study on page 50.

Australia: One Central Park, Sydney (116 meters, 34 stories, completed 2014)

Traditional residential tall buildings do not typically boast good energy performance. One Central Park breaks this mold, distinguished by its 5-kilometer-long system of hydroponic planters and cantilevered heliostats that track the sun to strategically redirect its rays (see Figure 2). These two strategies are particularly suitable for Sydney's temperate climate, which can border on subtropical. Through the use of hydroponics, the solar impact on apartments can be reduced by up to 20 percent from the polyethylene planter boxes, and an additional 20 percent from the shading of the vegetation. More than 180,000 plants on the building sequester CO_2, emit oxygen, and absorb heat. The planter boxes can be recycled, proving a better embodied energy performance than typical metallic louvers. Furthermore, water for the plants is provided by a 1-ML/day blackwater treatment facility, reducing the need to expend energy to pump fresh water.

The passive solar power system of One Central Park utilizes 42 heliostats and 320 fixed mirrors. These provide hours of sunlight and heating to areas normally shaded, and can even divert 50 percent of their reflected solar rays to partially heat the rooftop swimming pool (see Figure 3). This faceted reflector also serves as a shading device for the upper west façade of the tallest tower. As foliage cover is difficult to quantify, and the heliostat system does not actively generate energy, they are not recognized in Australia's BASIX or Green Star calculations, which recognize excellence in sustainability. One Central Park still achieves high marks in terms of sustainability certifications, through some of its less-visible measures, such as the deployment of a 30-megawatt central thermal plant and a 2-megawatt tri-generation system. Through these strategies, One Central Park is able to reduce its energy consumption by 26 percent compared to the average New South Wales building (Nouvel & Beissel 2014).

Middle East: Al Bahar Towers, Abu Dhabi (145 meters, 29 stories, completed 2012)

These twin towers attempt to address the effects of solar glare and heat gain in a desert climate, while also representing a local design aesthetic (see Figure 4). A traditional lattice screen from the area, the *mashrabiya*, was adapted, through parametric and algorithmic computer studies, into a series of operable, semi-transparent polytetrafluoroethylene (PTFE) panels on the façade (see Figure 5).

Each panel opens and closes depending on the sun's position, allowing light to enter the building (and views out) while blocking direct glare and heat gain. This reduces the building's need for artificial lighting and overall cooling loads, with estimated savings of 1,750 metric tons of CO_2 per year.

The overall building form was designed to complement this façade system, but also considered was the wall-to-floor area efficiency of a circular floor plate, saving on embodied emissions. Water in the building is also heated from a series of solar thermal panels, which help contribute to the building's LEED Silver certification (Wood & Henry 2012).

Central/South America: Torre Reforma, Mexico City (246 meters, 56 stories, completed 2016)

Like One Central Park and the Al Bahar Towers, Torre Reforma (see figures 6 and 7) must look for innovative strategies to cool the space in a predominantly warm climate. In this building, all rain and wastewater is 100 percent reused, primarily for air conditioning,

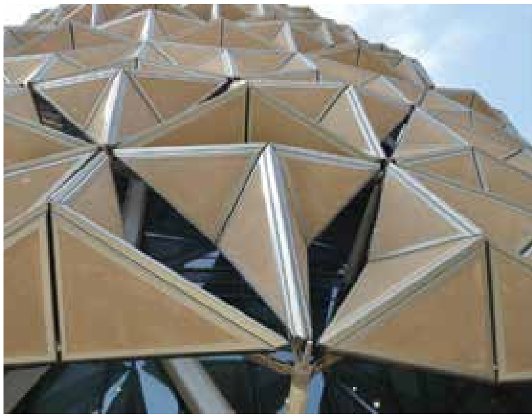

Figure 5. At Al Bahar Towers, Abu Dhabi, each panel opens and closes depending on the sun's position, allowing light to enter the building (and views out) while blocking direct glare and heat gain. © Terri Meyer Boake

Figure 6. Torre Reforma, Mexico City, uses its concrete shear walls to limit solar heat gain. © HEXA

Figure 4. The façade panels of Al Bahar Towers, Abu Dhabi, are representative of a *mashrabiya*, a traditional lattice screen used to shade buildings in the Middle East. © Still ePsiLoN (cc by-sa)

Figure 7. At Torre Reforma, Mexico City, concrete shear walls, perforated with slots, selectively admit light, while a double-layered glass façade supplies the building with natural ventilation. © HEXA

bathrooms, and street-level irrigation needs. The water storage tanks are dispersed along the tower, so gravity can be taken advantage of, instead of energy-intensive pumps. Further emission prevention measures are taken by way of the building's automatic parking systems, which don't need to be lit or ventilated, and no toxic vehicular exhaust is emitted, as cars are moved by electric lifts instead of their own engines.

In addition to the water pumps and robotic parking, concrete shear walls and double-layered glass façades work together to improve the minimum solar coefficient (SC), solar heat-gain coefficient (SHGC), u-value, reflection values, and light transmission levels well above that recommended by the American Society of Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE), and reduces overall energy use by 24 percent, compared to conventional buildings of this size (Boy 2017). Automatically controlled windows that open before dawn, and naturally-ventilated triple-height atria with vegetation further provide the building with a flow of cool air and improve the air quality.

Africa: Zeitz MOCAA, Cape Town
(58 meters, 14 stories, completed 2017)

By reusing the structure of an existing 90-year-old, abandoned grain silo, the Zeitz Museum of Contemporary African Art (MOCAA) saves significant embodied emissions, with only a 250-millimeter layer of new concrete needing to be cast directly onto the retained silo walls (see Figure 8). Further embodied emissions are saved by locally sourcing all labor and all façade materials, excluding specialized solar control glass. The cooling and heating requirements of the solar control glass were analyzed with computational fluid dynamics and effectively minimized the solar heat gain (see Figure 9).

The façade, specialized mechanical engineering, and thermal inertia from exposed

Figure 8. The Zeitz MOCAA project in Cape Town is an adaptive reuse of a former grain silo, significantly limiting the embodied energy required in its creation. © Matti Blume (cc by-sa)

Figure 9. The cooling/heating requirements of the solar control glass at Zeitz MOCAA, Cape Town, were analyzed with computational fluid dynamics and effectively minimized the solar heat gain. © soomness (cc by-sa)

Figure 10. China Resources Building, Hong Kong, incorporates modern HVAC technology and operational standards into a reused, existing structure, meaning that 97 percent of the total building envelope, structural core, floors, and roof of the existing building could be retained. © Wing1990hk (cc by-sa)

Figure 11. A façade detail view of China Resources Building, Hong Kong, which features a special low-e coating to limit solar gain. © Powfreytmn (cc by-sa)

concrete soffits all contribute to a precise system that reduces the power demand on the building and allows the humidity and temperature to be regulated, allowing particularly fragile artwork to be loaned to the museum and viewed in this space.

In addition to the actions taken by the building to reduce the energy load, additional heating and cooling is sourced from a precinct-wide system that uses nearby seawater as a heat source and a heat sink. The precinct-wide system was optimized with the Zietz MOCAA's MEP systems to maximize efficiency of the heating and cooling cycles (Archer & Brunette 2018).

Asia: China Resources Building, Hong Kong (178 meters, 50 stories, completed 1983, retrofitted 2013)
Like Zeitz MOCAA, the China Resources Building (see Figure 10) incorporates modern HVAC technology and operational standards into a reused, existing structure, meaning that 97 percent of the total building envelope, structural core, floors, and roof of the existing building could be retained. Furthermore, a construction-waste management plan was implemented, allowing 1,977 metric tons of waste, or 81.3 percent of the total construction waste, to be recycled or reused. Also like the previous example, the China Resources Building takes advantage of its location near Victoria Harbour to incorporate a seawater-cooled chiller plant into the building, which uses about 20 percent less energy than traditional air-cooled chiller plants.

> “At China Resources Building, Hong Kong, 81.3 percent of the total construction waste was recycled or reused.”

Additional upgrades to the façade and lighting presented additional operational emissions savings (see Figure 11). A special low-e coating was applied to the glazing to reduce solar heat gain. Light-emitting diode (LED) fittings and energy-efficient fluorescents were used; both require less maintenance and have longer life spans than traditional T8 light fittings (Wan, Cheung & Cheng 2015).

Europe: Stadthaus, London (30 meters, 9 stories, completed 2009)
Completed in 2009, Stadthaus was one of the first modern tall buildings to use cross-laminated timber (CLT) panels (see figures 12 and 13). As timber is a carbon sink, capturing carbon that otherwise would have been released into the atmosphere by a dying tree, constructing tall buildings of timber elements can play a

Figure 12. Completed in 2009, Stadthaus, London, was one of the first modern tall buildings to use cross-laminated timber (CLT) panels. © Will Pryce

Figure 13. An interior, under-construction view of Stadthaus, London, reveals the aesthetics and simplicity of using timber paneling, panel construction, adding to its value as a carbon sink. © Will Pryce

significant role in reducing embodied energy consumption.

CLT panel construction is analogous to the wooden formwork that encloses pre-cast concrete—but without the concrete, and all of its attendant environmental concerns. Also unlike concrete, CLT panels can be disassembled and recycled at the end of their service life. Once a CLT building can no longer perform its intended function, the modular nature of a panelized system allows for repairs or modifications to be made relatively easily. The wooden structure of the Stadthaus tower stores more than 188 metric tons of carbon-dioxide equivalent. Additionally, by not using a reinforced concrete frame, another 124 metric tons of carbon dioxide was never produced, and therefore never entered the atmosphere. This is equivalent to 21 years of carbon that would have been emitted by construction of a conventional building of this size.

With respect to operational carbon, CLT acts as a thermal envelope, being a solid but air-filled surface. When combined with rigid insulation, wood cladding, and taped plasterboard, CLT is quite effective as an insulator and mitigator of drafts. That said, CLT wall systems are breathable and resistant to mold growth, and when paired with high-functioning mechanical and air management systems, can produce an indoor environment that supports occupant health (Northrup 2010).

North America: Bank of America Tower, New York City
(366 meters, 55 stories, completed 2009)

Notable for its scale and prominence as a corporate headquarters in a major city, the Bank of America Tower's advanced technologies include a clean-burning, on-site, 5-megawatt cogeneration plant, which provides approximately 65 percent of the building's annual electricity requirements and lowers daytime peak demand by 30 percent (see Figure 14). A thermal storage system further helps reduce peak load on the city's overtaxed electrical grid by producing ice at night, which is melted during the day to provide cooling (see Figure 15). Nearly all of the 1,200 millimeters of annual rain and snow that fall on the site are captured and re-used as graywater to flush toilets and supply the cooling towers. These strategies, along with waterless urinals and low-flow fixtures, save approximately 7.7 million gallons (29 million liters) of potable water per year.

Recycling was a prominent factor throughout the building's construction, with 91 percent of construction and demolition waste diverted from landfills. Materials include steel made from 75-percent (minimum)-recycled content, and concrete made from cement containing 45-percent-recycled content (blast furnace slag). To protect indoor air quality (IAQ) as well as natural resources, interior materials are low-volatile organic compound (VOC), sustainably harvested, manufactured locally, and/or recycled wherever possible.

The building's exceptionally high IAQ results from hospital-grade, 95 percent filtered air; abundant natural daylight and 2.9-meter ceilings; an underfloor ventilation system with individually controlled floor diffusers;

round-the-clock air quality monitoring; and views through a clear, floor-to-ceiling glass curtain wall. This high-performance curtain wall minimizes solar heat gain through low-e glass and a heat-reflecting ceramic frit; it also has allowed the Bank of America Tower to reduce artificial interior lighting by way of an automated daylight dimming system, reducing lighting and cooling energy consumption by up to 10 percent (Wood and Henry 2011).

Conclusion

It is beyond question that there is a strong imperative for the building industry to dramatically reduce its carbon footprint within just a few years. It is also plainly evident that a collection of stellar best-case examples, as presented here, will not, on its own, drive cities to meet the climate obligations of the Paris Agreement, C40, or any other initiative. But it is nevertheless the obligation of the building industry and government leadership to understand in as much detail as possible the potential of wholesale changes in approaches to construction, in order to make significant progress in the battle to reduce the impact of climate change on the cities that continue to grow. Without a demonstration of the possible, there will be no progress. It will only be through a combination of best construction and operational practices, transportation and planning policy, energy policy, and political will across the vast diversity of the built environment that the odds will begin to turn in favor of climatic improvement. ■

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Figure 14. The high-performance curtain wall of Bank of America Tower, New York City, minimizes solar heat gain through low-e glass and a heat-reflecting ceramic frit. © Marshall Gerometta

Figure 15. Ice storage tanks in the basement of Bank of America Tower, New York City. Ice created overnight is melted during the day to provide cooling. © Marshall Gerometta