Title: **The Zero-Carbon Hybrid Future of Tall Timber**

Authors: Craig Applegath, Founding Principal, DIALOG
Cameron Veres, Principal, DIALOG
Thomas Wu, Principal, DIALOG

Subjects: Architectural/Design
Building Materials/Products
Sustainability/Green/Energy

Keywords: Construction
Structure
Timber

Publication Date: 2021

Original Publication: The Zero-Carbon Hybrid Future of Tall Timber

Paper Type:
1. Book chapter/Part chapter
2. **Journal paper**
3. Conference proceeding
4. Unpublished conference paper
5. Magazine article
6. Unpublished

The Zero-Carbon Hybrid Future of Tall Timber

Craig Applegath

Cameron Veres

Thomas Wu

Authors

Craig Applegath, Founding Principal
Cameron Veres, Principal
Thomas Wu, Principal
DIALOG
500, 35 John Street
Toronto, Ontario M5V 3G6
Canada
e: capplegath@dialogdesign.ca
dialogdesign.ca

Craig Applegath is a Senior Architect at DIALOG and Founding Principal of the firm's Toronto studio. He is a passionate designer who believes in the power of built form to meaningfully improve the well-being of communities and the environment they are part of. A noted advocate of density, sustainable building design, and urban regeneration, and a renowned expert in urban resilience, Applegath was a founding Board Member of Sustainable Buildings Canada and is currently Acting Chair of the Mass Timber Institute.

Cameron Veres is a Principal and Senior Architect at DIALOG, with a focus on how technology is changing architecture and city-making. Veres leads the development and use of new technologies that help the firm communicate and collaborate better; reduce costs and inefficiencies; bridge the gap between design and construction; and expand the possibilities of design. As one of the leaders in DIALOG's commercial, retail, and mixed-use sector team,Veres has a design focus on high-rise development.

Thomas Wu, PhD is a Principal and Senior Design/Project Engineer at DIALOG. Leveraging a Doctorate of Philosophy in Civil Engineering from Michigan State University, Wu has focused on the complexities of designing and constructing commercial and residential high-rise buildings throughout his 35-year career. During his time at DIALOG, he has played a major role in developing the iconic skyscraper skyline of Vancouver, including Fairmont Pacific Rim, Shangri-La Vancouver, and Shaw Tower.

Abstract

A patent-pending Hybrid Timber Floor System (HTFS), with a prefabricated composite floor panel, offers significant advantages over traditional building technology. It is capable of clear floor spans of up to 12 meters; reduced structural floor thickness; higher and more consistent quality; reduced construction time; greater occupant safety; more exposed wood; and superior sustainability attributes. The HTFS is the starting point for a supertall zero-carbon hybrid timber building prototype design, with a concrete core and diagrid steel external structure. The prototype leverages energy efficiency, smart technologies, façade-integrated photovoltaics (PV), and a district energy cogeneration plant combined with an algae bioreactor, to achieve zero operational carbon on-site. Excess energy is provided to the surrounding neighborhood in a "net(work)-zero" carbon strategy, and a vision for future zero-carbon embodied energy is also outlined. This supertall prototype is a response to the oft-posed question: Can this type of construction ever be truly sustainable?

Keywords: High-Rise, Hybrid Construction, Mass Timber

Introduction

The Hybrid Timber Tower (HTT) prototype for Toronto, outlined in this paper, demonstrates that supertall buildings can be a catalyst for a dense, decarbonized future (see figures 1 and 2). Designed with a new patent-pending Hybrid Timber Floor System (HTFS), this prototype suggests that, while "zero-carbon supertall" buildings are already very much within the realm of the possible, the pursuit of all-timber "purity" is best abandoned if we want to meet our climate commitments.

The challenge to building tall with timber is inherent to the material itself: we are asking wood to do things it was not designed to do. Wood becomes a more inefficient structural material at greater heights, which is why hybrid solutions are more common in taller buildings. Further, tall all-wood mass timber structures require an uneconomical volume of wood to replicate the structural capacities of steel and concrete; this limits its use in tall buildings. Wood suffers from much greater shrinkage and creep than steel and concrete, which makes its use as vertical structure in combination with concrete cores and aluminum curtain wall systems very problematic. Engineered wood products are currently not able to achieve the necessary

Figure 1. Street view of Hybrid Timber Tower, Toronto, looking north at dusk. This supertall zero-carbon hybrid timber building prototype is designed with a concrete core and diagrid steel external structure, and leverages energy efficiency, smart technologies, façade-integrated photovoltaics (PV), and a district energy cogen plant, combined with an algae bioreactor, to achieve zero operational carbon on-site.

column-free floor spans to accommodate typical commercial floor plates. Even though mass timber structural systems are designed with a sacrificial char layer to protect the structural member from fire, its use is limited in tall residential buildings where codes in many jurisdictions require most, if not all timber to be covered with a fire-rated material such as drywall. Lastly, the market for sustainable mass timber remains small, increasing costs and providing little incentive for sustainable timber harvesting practices. As designers and builders, we need to address these barriers.

The Hybrid Timber Floor System

It seems floor systems represent the greatest opportunity for mass timber from an environmental perspective. A structural life cycle analysis (LCA) revealed that floor systems contribute the lion's share of total environmental impact in high-rise buildings, ranging from 32 percent to a whopping 73 percent (Lankhorst et al. 2019). Another recent LCA study suggested that incorporating responsibly sourced CLT composite decks in combination with glulam beams could reduce embodied carbon by 73 percent in a 26-story building—the CLT composite deck alone delivering a 68 percent reduction (Drew & Quintanilla 2017). Clearly, timber floor systems have the potential to deliver oversized reductions to environmental impact.

The authors' team set about addressing an unmet need: a hybrid timber floor system that offers open spans and fire safety, so it can be integrated into any building typology. The resulting prefabricated, composite HTFS leverages the properties of concrete and steel to reinforce the engineered timber—post-tensioning cables and steel cages are encased in a concrete band and recessed into a CLT wood panel. This allows for greater spans of up to 12 meters (40 feet), offering the open floor plate required for Class-A office commercial floor space; current CLT wood panel spans are restricted to about 8 meters (26 feet). It also improves fire safety, because the panels allow exposed wood to char during fire breakout, creating protective char layers for the remaining wood layers (Lam et al. 2013, Karacabeyli & Gagnon 2019), while the non-combustible concrete and steel band continues to support the uncharred wood panel with its composite action (see Figure 3).

Figure 2. Proposed site is located at the northern end of the Toronto Yonge Street subway line. The prototype would serve as a key node of dense, transit-oriented development in a largely suburban environment, and provide an important focal point to anchor future development of density along the North-South transit system.

Hybrid System Benefits

There are several other important benefits.

First, because the panel's sectional depth is less than typical steel-and-concrete or all-concrete floor systems, the HTFS offers a lower floor-to-floor height; this can provide additional floors or a reduction in building height, decreasing the overall cost of cladding systems, finishing, erection, and operating costs.

Second, the mass timber can be exposed (see Figure 4). There are studies that suggest people prefer spaces with exposed wood (Sakuragawa et al. 2005, Rice et al. 2006).

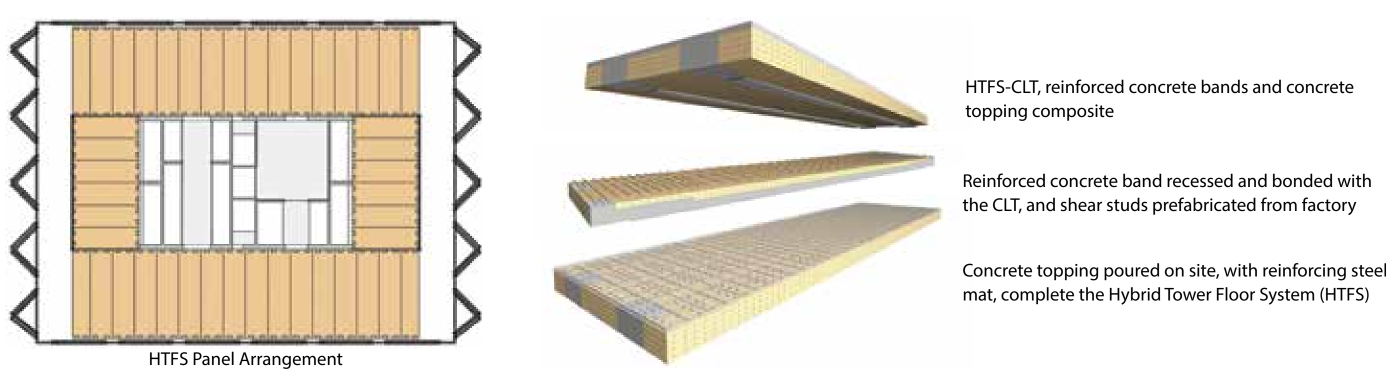


Figure 3. The patent-pending Hybrid Timber Floor System (HTFS), is a composite floor system that consists of cross-laminated timber (CLT), post-tensioned concrete band and reinforced concrete topping, designed to provide for clear spans of 12 meters, allowing for open floor plates required for Class-A office commercial floor space.

Figure 4. Interior main lobby view. Here, the use of mass timber becomes a powerful aesthetic element.

Annual Building Loads by End-Use	
Algae Bioreactor (MWh)	4,380
Interior Lighting (MWh)	3,325
Plug and Process (MWh)	6,335
Space Heating Load (MWh)	5,331
Service Water Heating (MWh)	4,016
Interior Central Fans (MWh)	598
Interior Local Fans (MWh)	975
Pumps (MWh)	835
Cooling Load (MWh)	12,217
Total	**38,012**

Annual Facility Energy Demands	
Building Electricity Consumption (MWh)	16,448
Electric Cooling Plant—Electricity Consumption (MWh)	2,387
Residual Cooling Load (MWh)	5,753
Residual Heating Load After Heat Recovery (MWh)	5,984
Total	**30,572**

Annual Energy Supply	
CHP Waste Heat Used to Offset Heating Loads (MWh)	5,984
CHP Waste Heat used to Offset Cooling Loads Via Absorption Chillers (MWh)	5,753
CHP Electricity Generation (MWh)	13,816
PV Electricity Generation (MWh)	4,557
Backup Generator Electricity Generation (MWh)	462
Total	**30,572**

Table 1. Energy demand and supply calculations for Hybrid Timber Tower.

> “The HTT could sequester over 36,000 metric tons of carbon-dioxide equivalent emissions, comparable to taking more than 7,900 cars off the road for a year.”

Third, given that the floor cycle (number of floors that can be completed in a period of time) dictates overall construction time, it is possible this system could be as fast as a steel-and-concrete system to erect.

Fabrication and Feasibility

The HTFS floor panels have been designed to fall within existing CLT industry fabrication limits, and each panel section, at 3 meters in width, can be transported by flatbed truck and assembled on-site. The estimated weight of a panel would be shy of 9,000 kilograms, which informs the selection of tower cranes. There are still various manufacturing details to be considered, such as different trenching and block-gluing configurations, optimized screwing methods for the array of fasteners, and building out a streamlined supply chain for high-volume manufacturing.

Even with a number of unknowns, the authors estimate that the HTFS would represent a cost premium of approximately 30 percent for the structure, resulting in a 10 to 15 percent premium for the total project. This premium is relatively in-line with some other structural innovations being developed around the world today, and would be expected to significantly decrease as the supply chain for sustainable mass timber becomes more robust. Widespread global adoption and enforcement of carbon off-set credits could also significantly reduce the net cost of the HTFS. With constructability ascertained, the next logical step was to design a prototype.

A Zero-Carbon Hybrid Tower Prototype

There is a strong incentive to demonstrate that zero carbon at this height is possible. Net-zero energy, in which all energy is generated by renewables on-site, has proven to be challenging, particularly in dense urban areas; there has been a focus instead on net-zero carbon, in which renewable energy can be generated both on-site and off-site, combining for zero carbon. However, there is a flaw in this logic, as the building is unable to achieve this feat in isolation.

The HTT aims to overcome this flaw by achieving zero carbon entirely within the building itself, and entirely off the grid. This is achieved by deploying photovoltaics (PV) on the east, south, and west façades, and using a natural-gas-powered district energy combined heat and power (CHP) plant to provide the power, heat and cooling not provided by the PVs (see Figure 6). The combustion emissions from the plant, including carbon dioxide, nitrogen oxides, and sulphur oxides, will be captured and sequestered by an algae bioreactor.

Hybrid Mass Timber

The design approach for this prototype was to work to the strengths of each structural material: concrete core, steel frame, and hybrid mass-timber floors. The concrete core and elevator system were designed based on existing supertall buildings to support an appropriate fire safety strategy (see Figure 5). The steel frame is an efficient diagrid structure, which can reduce environmental impact by up to 41 percent, compared to traditional tube structures (Lankhorst et al. 2019).

The HTFS completes the structural elements of the prototype. In total, there are more than 36,649 cubic meters of sustainably harvested mass timber in the HTT prototype; compare this to 2,600 cubic meters in Mjøstårnet, Brumunddal, Norway, the current tallest mass-timber building (Abrahamsen 2017). One cubic meter of wood product can potentially store 1.9 tons of carbon dioxide equivalent (tCO_2e) (Sathre & O'Connor 2010), but even at a more conservative standard of 1 tCO_2e per m^3 of timber (Van der Lugt 2012), the HTT could sequester over 36,000 metric tons of carbon-dioxide equivalent emissions, comparable to taking more than 7,900 cars off the road for a year (EPA 2020).

Supertall Over a Subway

Imagined as the symbolic gateway at the northern edge of the City of Toronto (see Figure 7), the HTT would be the tallest building in the city at 105 stories, even among those proposed and under construction (Alexander 2020). The prototype would serve as a key node of dense transit-oriented development in a largely suburban environment and provide an important focal point to anchor future development of density along the north-south transit system.

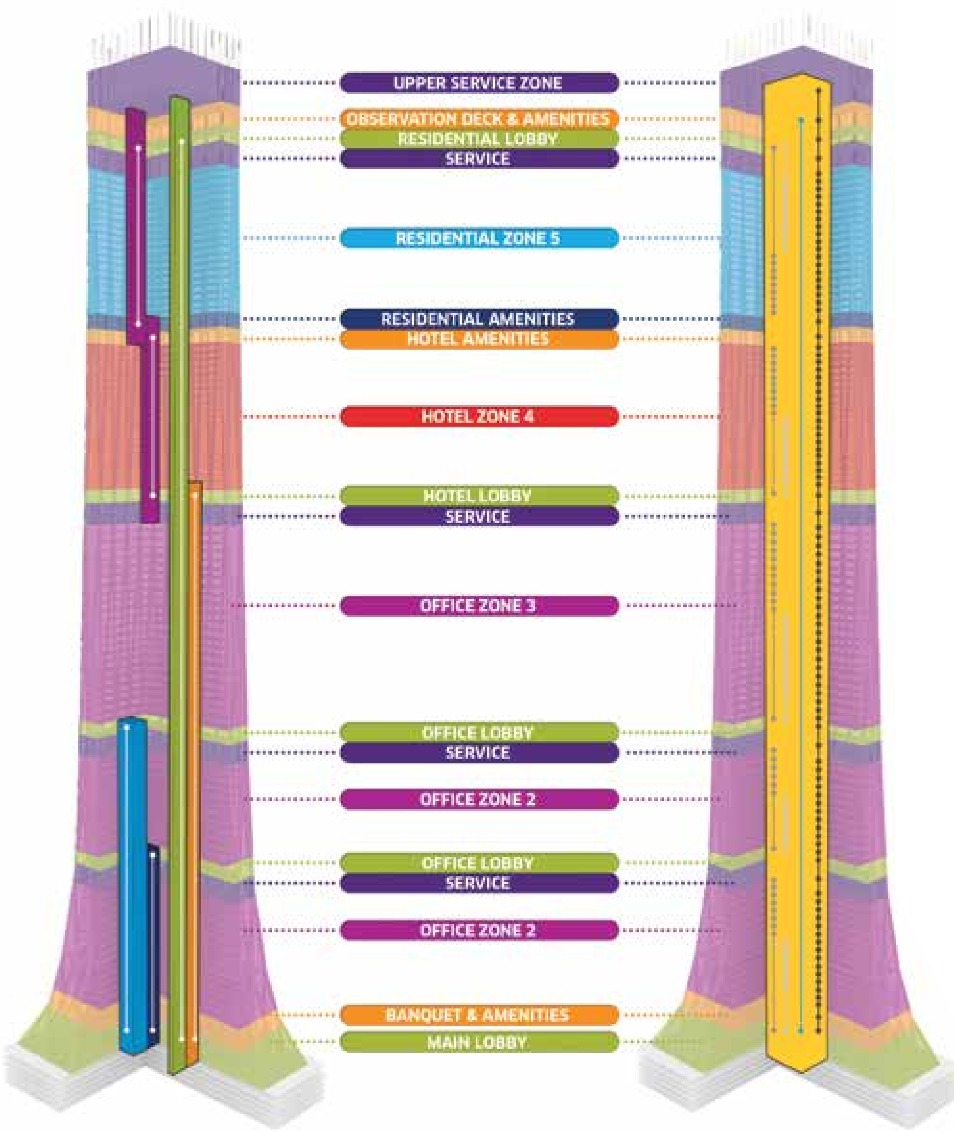


Figure 5. Building program and vertical transportation diagrams.

Figure 6. Birds-eye view, looking down past the tower at the site below. The open space directly to the east of the tower is at the same scale as the tower itself, mirroring the structure's verticality with a long horizontal green space that forms a symbiotic relationship with the structure. The envisioned open space acts as needed relief for users, supporting health and well-being with meandering paths and access to greenhouse farms, strategically integrated into the landscape.

Figure 7. Interior vertical landscape. As seen from below, bands of landscape rise up between the outer skin and the interior spaces, expanding into the lower skylobbies of the tower.

Figure 8. View of tower and landscape looking west. Note the winter garden greenhouses integrated into the landscape that provide food for the tower residents, as well as the surrounding neighborhood.

Addressing Health Outcomes Through Design

COVID-19 has raised important questions about density and mass transit; both are still essential as we face the ongoing climate crisis, so we must design differently for density in a post-COVID-19 world. This prototype features a few key interventions to begin the conversation: natural ventilation can be provided through the double-skin envelope; all services can be performed and segregated within the core; and all touchable hardware and surfaces—including the exposed columns at the lower level—are solid or plated bronze to kill microbes (Warnes et al. 2012). Open floor spans without columns, such as those offered by the HTFS, will be even more critical in offices where distancing is required.

Horizontal into Vertical Landscapes

The open space to the east of the tower is at the same scale as the tower itself, mirroring the structure's verticality with a long horizontal landscape that forms a symbiotic relationship with the structure (see Figure 8). The open space acts as a needed place of rest for users, supporting health and well-being with meandering paths and access to indoor farms, strategically integrated into the landscape, that contribute to food security for the building and the surrounding neighborhood. Both landscape and farm move up through the tower (see Figure 9), with bands of landscape rising up and expanding into the lower skylobbies, while an indoor vertical farm provides fresh, hydroponically-grown greens year-round directly to the restaurants and hotel. The interface at the base of the building features a plaza and green space (see Figure 10).

Managing Wind Like a Tree

Wind plays an outsized role in design of tall structures. Unlike the current trend of shaping supertalls curvaceously to reduce vortex turbulence, the HTT prototype is shaped orthogonally, gently curving out to meet the ground, very much reminiscent of how a tree trunk performs the same task as it meets the earth. This building form strategy offers several benefits: First, it maximizes the efficient use of mass timber in the rectangular HTFS. Second, a rectangular floor plate provides greater usability and efficiency for office planning. Third, the shape better integrates into Toronto's existing rectangular street grid. Lastly, it is significantly more cost-effective to deal with wind loading by introducing intermediate open "blow-through" floors, which allow wind to move through the building, than to curve floor plates.

The structure was opened up at the five truss floors that connect the steel diagrid to the concrete core, in order to mitigate vortex-shedding-induced motion. A 50-percent porous screen was specified at the top of the tower—again, this is analogous to how a tree manages wind (see Figure 11). A pair of tuned mass dampers at the top of the tower will be an integrated feature of the observation deck experience.

The Envelope and Façade-Integrated PV

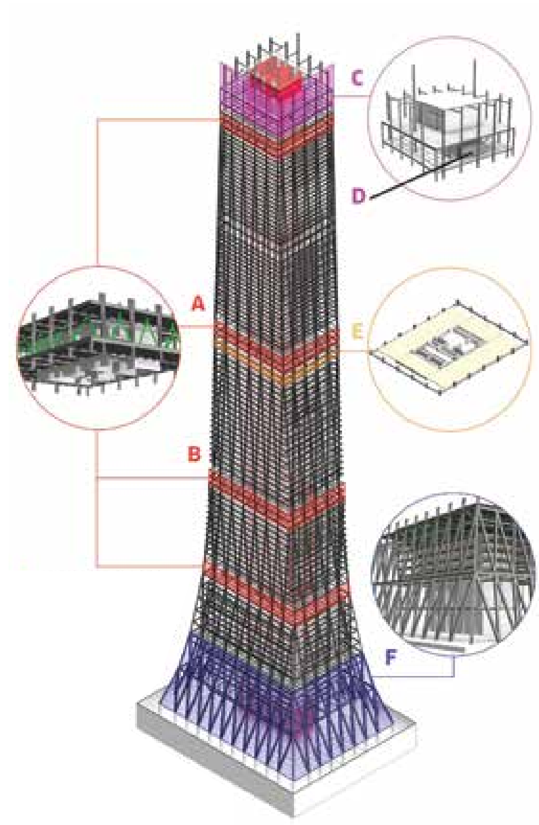
The skin of the building has been designed for both energy conservation and energy production. The façade responds to the structure; it is designed to work on a story-by-story basis. As the building rises in height, the façade will react optimally to orientation and climatic conditions. It is designed to allow localized consolidation of multiple floors to create multistory, interconnected amenity spaces. Coupled with an automatically controlled, active solar shading system, complete with integrated PVs, the box-frame double-skin curtain-wall system provides an ultra-high-performance building façade that enhances natural daylight penetration and promotes natural ventilation through manual controls.

The integrated façade PV system balances output and daylighting using a combination of optical PV blinds for the glazing sections and opaque PV modules for wall/spandrel sections, connected to a battery energy storage system (BESS) that provides the building with 4,557 MWh of electricity, or 24.2 percent of its projected annual electricity demand (see Figure 12). Sensor-based smart systems help reduce electricity demand further, by measuring demand in real time.

Vertical District Energy

Given the scale of this prototype and the fact that stacked building types—retail, commercial, hotel, and residential—stagger energy usage times, a district energy cogeneration solution is selected (see Figure 13). Energy modeling shows the prototype requires 18,835 MWh of electricity, 12,217 MWh of cooling, and 9,347 MWh of heating per annum (5,984 MWh after heat recovery from the urban farm and data center). In addition to the power supplied by the PV, the CHP will provide 73.4 percent of the electricity, with 2.5 percent from the backup generator on peak days. All thermal load requirements will be supplied from the CHP plant. The absorption chillers, powered through waste heat, will provide 47.1 percent of the cooling demand, with the remaining cooling provided by the electric chiller plant, already captured under the electric load. In sum, this supertall is completely energy self-sufficient, reducing grid strain and adding resilience.

It should be noted that using natural gas (methane) makes sense in the Canadian context, because Canada has abundant gas resources. But more importantly, during a transition to renewable energy, we will need to find carbon-neutral ways to use fossil fuels. The design accomplishes this by



A -Outrigger floors
B -Partial opening through outrigger floors to minimize wind impact
C -Tower crown
D -Mass tuned dampers
E -Typical hybrid timber floor system (HTFS)
F -Framing for open lobby

Figure 9. Overall structural system diagram, illustrating the critical structural elements that are essential to the design of the 105-story supertall Hybrid Timber Tower. This design is a combination of wood, concrete, and steel, demonstrating how wood can be used in mainstream mixed-use buildings, at a scale that is unprecedented.

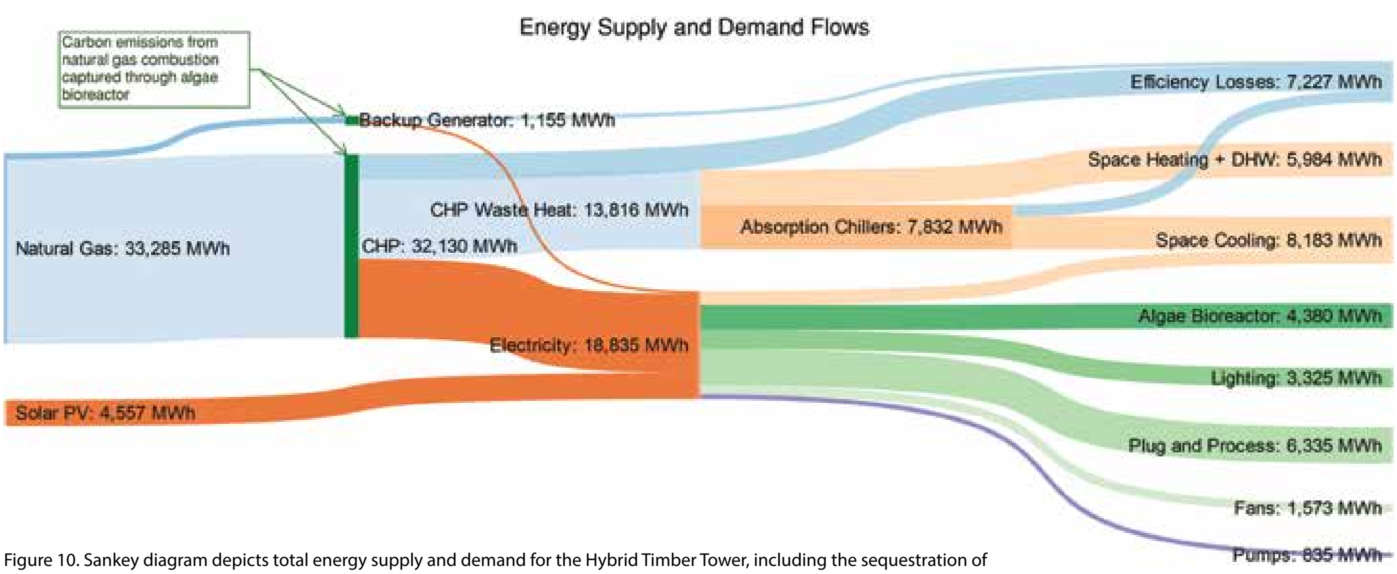


Figure 10. Sankey diagram depicts total energy supply and demand for the Hybrid Timber Tower, including the sequestration of natural gas by the algae bioreactor.

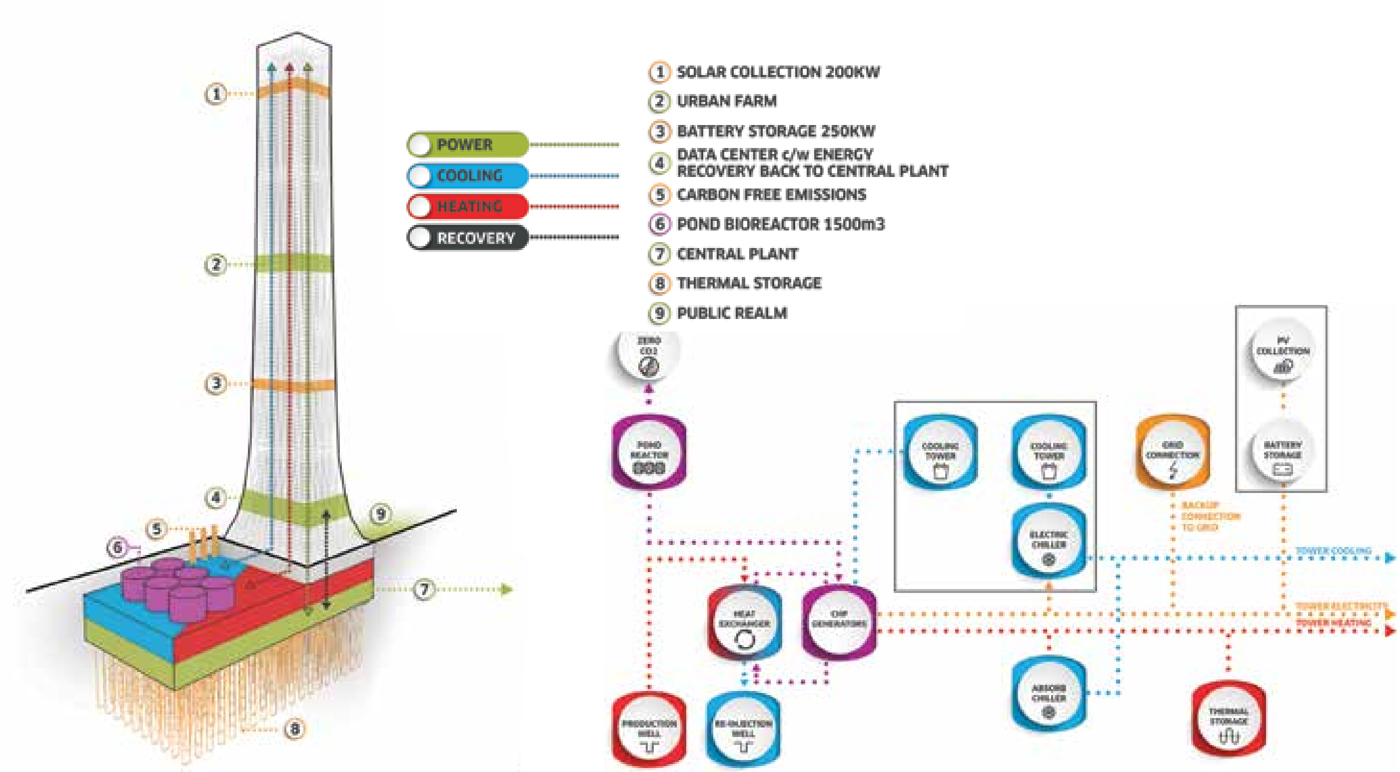


Figure 11. Energy and carbon flow diagram, illustrating the integration of the energy generation, heating, and cooling systems, as well as CO_2 emissions sequestration. The prototype leverages energy efficiency, smart technologies, façade-integrated photovoltaics (PV), and a district energy cogeneration plant, combined with an algae bioreactor to achieve zero operational carbon on-site.

integrating a highly innovative algae bioreactor into the system that allows the building to use fossil fuel without generating carbon dioxide emissions. Furthermore, using a multi-fuel district generator supports the transition to renewables, as these plants are able to use natural gas, biomass, renewable energy, or waste energy.

Universal Flexibility

The energy loads were simulated under typical meteorological conditions for Toronto City Centre (CWEC 2016 weather simulation file) using a whole-building energy model developed using IES-VE modeling software. The HTT is cooling load-dominated even though it's located in ASHRAE climate zone 5 (cold, humid) due to high solar loads through the building envelope and process cooling loads associated with the data center and the urban farm. The HTT is adaptable to any local climate, as this system provides universal flexibility: waste heat can be used to offset either heating or cooling loads.

The Algae Bioreactor

The technology that allows this district energy system to run as "carbon-neutral" is an algae bioreactor. The bioreactor comprises a series of tanks that use water, a highly efficient proprietary LED lighting system, and the carbon dioxide from fossil fuel combustion emissions from the CHP plant, to grow algae that sequesters the carbon dioxide (see Figure 14).

The combustion emissions can be injected into the algae bioreactor in two ways. The first method is to bubble the carbon dioxide and other flue gases from the CHP generator through the water in the reactor tank. Thusly, the algae captures up to 80 percent of the carbon dioxide, releasing the rest into the atmosphere. The second, more effective method, is to inject the gas into a carbonized column, with pressurized gas actively forcing all of the emissions to dissolve into the water, making them more accessible to the algae. This scenario reduces the carbon dioxide level by over 99 percent, and gets the prototype to zero carbon, capturing the 5,783 tCO_2e produced by the CHP annually. Smog-causing nitrogen oxides and sulphur oxides are also captured by the algae.

The district energy plant and the 1,500 cubic-meter (396,000-gallon) algae bioreactor are co-located in the basement of the tower, but one or more of the algae tanks can be placed in the lobby, allowing some of the light to shine through (see Figure 15). Additionally, by revealing the system, the science is on display.

Net(work)-Zero Carbon

The CHP-plus-bioreactor combination can be scaled to produce excess zero-carbon energy for future mixed-use development in the neighborhood. This would transform the tower into a central hub in a "net(work)-zero"

Figure 12. An algae bioreactor tank. Carbon dioxide (CO_2), nitrogen oxides (NOx), and sulphur oxides (SOx) are injected into a carbonized column inside the water tank, acting as a feedstock for the blue-green algae when combined with a highly-efficient LED lighting system to stimulate photosynthesis. © Pond Technologies Inc.

carbon community that could help cities meet their targets for carbon neutrality.

Towards Zero Carbon, Embodied

Embodied carbon is responsible for 28 percent of building sector emissions and 11 percent of total annual greenhouse emissions (UNEP 2017). A life cycle analysis of the HTT, (structure only) showed total embodied carbon at 40,665 tCO_2e—including biogenic carbon—compared to a baseline design with a steel deck and concrete floors at 75,413 tCO_2e. This represents a 46 percent reduction of embodied carbon.

However, there is still a significant gap to zero carbon embodied. In the future, technology like the algae bioreactor may bridge the gap. A 22.5 cubic-meter (6,000-gallon) bioreactor currently being piloted at St. Mary's Cement in Ontario, Canada, captures 1,000 metric tons of carbon dioxide of the 300,000 metric tons emitted each year—and this plant is small by industry standards. The challenge is scale.

The Future of Zero-Carbon Supertall

The HTT prototype demonstrates that it is possible to design and build a net-zero carbon supertall, dispelling the notion that this type of building is a myth. Leveraging technologies such as the HTFS, façade-integrated PV, and an algae bioreactor connected to a CHP, carbon emissions from operations were effectively reduced to zero and embodied carbon was significantly reduced.

However, there is still much work to be done, particularly on the embodied carbon front. The promise of mass timber depends on the creation of an industry based on sustainable forestry; further research and development in this area is crucial. It will also be critical to decarbonize steel and concrete production as these materials will continue to be essential in the construction of tall buildings; the growth of a mass timber industry may help spur necessary changes. Finally, it will be important to explore how natural capital can contribute to net-zero carbon—or even climate positive—supertalls in the future. ■

Unless otherwise noted, all image credits in this paper are to DIALOG.

Figure 13. Algae bioreactor in ground-floor lobby. Part of the bioreactor is exposed in the lobby, allowing light to shine through light portholes, revealing the algae growing in response to light and emissions from the natural gas cogen plant, as part of a "science on display" education strategy.

Acknowledgments

The authors would like to acknowledge the following partners on the Hybrid Timber Tower prototype:
EllisDon: Constructability analysis
RWDI: Building wind analysis
Cadillac Fairview: Property development insights
Morgan Solar: Solar opportunity assessment using MSI Sun Studio software
Pond Technologies Inc.: Algae bioreactor technology.

The authors would also like to thank the following firms and individuals for their contributions:
RDH: Building envelope technology insights
Structurlam, BBR Canada, and MTC Solution: HTFS constructability analysis
Mike Lawton: Urban farming strategies;
Tango Visual Studio: Building renderings
Thomas Hirschman: Editorial advice and contributions

References

Abrahamsen, R. (2017). "Mjøstårnet – Construction of An 81 M Tall Timber Building." Paper presented at the Internationales Holzbau-Forum (IHF) 2017, Garmisch-Partenkirchen, Germany, 6–8 December 2017.

Alexander, D. (2020). "Building Boom Set to Vault Toronto Past Chicago in Skyscraper Rankings." Accessed on 4 May 2020. https://www.bloomberg.com/news/articles/2020-01-09/toronto-building-boom-set-to-lift-city-s-skyscraper-ranks-chart.

Drew, C. & Quintanilla, N. (2017). "The Path to Life Cycle Carbon Neutrality in High Rise Buildings." *International Journal of High-Rise Buildings* 6(4): 333–43.

Karacabeyli, E. & Gagnon, S. (eds.) (2019). *Canadian CLT Handbook*. 2019 Edition. Pointe-Claire: FPInnovations.

Lam, F. et al. (2013). *Fire Resistance of CLT Wall and Floor Elements – Summary Data Report*. Vancouver: University of British Columbia.

Lankhorst, G., Arts, J., Terwel, K. & Jonkers, H. (2019). "Life Cycle Analysis: Load-Bearing Structures of High-Rise Buildings in Western Europe." *CTBUH Journal* 2019 Issue II: 28–35.

Rice, J.; Kozal, R.; Meitner, M. & Cohen, D. (2006). "Appearance Wood Products and Psychological Well-Being." *Wood and Fibre Science* 38(4): 644–59.

Sakuragawa, S., Miyazaki, Y., Kaneko, T. & Makita, T. (2005). "Influence of Wood Wall Panels on Physiological and Psychological Responses." *Journal of Wood Science* 51: 136–40.

Sathre, R. & O'Connor, J. (2010). "Meta-Analysis of Greenhouse Gas Displacement Factors of Wood Product Substitution." *Environmental Science & Policy* 13(2): 104–14.

United Nations Environment Programme (UNEP) & International Energy Agency (IEA). (2017). *Global Status Report 2017*. Nairobi: UNEP.

Van der Lugt, P. (2012). "Carbon Storage Utilising Timber Products." *Environment Industry Magazine* 22: 76-80.

Warnes, S. L.; Caves, V. & Keevil, C. W. (2012). "Mechanism of Copper Surface Toxicity in Escherichia Coli O157:H7 and Salmonella Involves Immediate Membrane Depolarization Followed by Slower Rate of DNA Destruction which Differs from that Observed for Gram-Positive Bacteria." *Environmental Microbiology* 14(7): 1730–43. https://doi.org/10.1111/j.1462-2920.2011.02677.x.