Adaptive Reuse as Carbon Adaptation: Urban Food Production in the Underused Parking Garages of the Future

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This research collaboration between the Circular City + Living Systems (CCLS) research lab and the architecture practice Weber Thompson addresses the intersection of three critical topics affecting the carbon footprint of the built environment: adaptive reuse of existing buildings, increased availability of electric and autonomous vehicles, and food production in cities. This study measures and compares the relative impact of the operational carbon impact reduction of an eventual transition to electric autonomous vehicles, the embodied carbon reduction of adaptive building reuse, and the potential to sequester carbon as a benefit from living systems in urban aquaponics operations in adapted parking garages.

Aquaponics, the combination of aquaculture and hydroponic growing systems, optimizes food, water, energy, and waste flows and reduces the need for resource input through high efficiency, cyclical exchanges. Integrating and scaling up aquaponic food production systems into cities provides an innovative approach to producing sustainable urban food and mitigating urban environmental challenges.

Through case study research, resource and scale analysis, this project leverages collaboration between practice and academia to explore the carbon impact of a promising near-future adaptive reuse of parking garages for urban food production. The relative embodied carbon impacts of adaptive building reuse, operational carbon reduction of transition to autonomous electric vehicles, and sequestration of carbon through urban aquaponics operations are measured and compared to advance and assess the viability of an innovative adaptive reuse concept.

INTRODUCTION TO RESEARCH TOPICS

This investigation addresses the intersection of three critical topics shaping the carbon footprint of the built environment: changing transportation trends, adaptive reuse of existing buildings, and food production in cities. Several transportation trends are shaping a future in which parking garages intended for single occupancy vehicles may sit largely empty. In our case study city, Seattle, Washington, much of the city can currently be accessed by public transportation. Ridership of municipal and regional bus and rail lines has grown 60% since 2002 and is still on the rise as planned expansions will provide access to more riders over the next 30 years (Federal Transit Administration). Additionally, predicted transitions to the increased use of electric and autonomous vehicles will affect the need for parking spaces, reshaping the landscape of urban transportation and corresponding carbon emissions (Project Drawdown).

The first aspect of this assessment is the future transition from gas powered vehicles to electric vehicles (EVs). In Seattle, as well as within other regional electric grids that are decarbonizing, the impact of using an individual electric car is primarily via the shift from fossil fuel use to clean electricity. For individual vehicles, the lifecycle carbon impact of EVs is estimated to be a 50% improvement compared to conventional gas vehicles (Hall and Lutsey 2018, Carbon Brief 2019). The City of Seattle estimated in 2016 that conventional cars and light passenger trucks accounted for nearly 1.8 million tons of CO_2 (City of Seattle 2016). With Seattle's clean power grid, that carbon impact can be reduced to nearly zero when shifted from fossil fuels to electricity (Seattle City Light). In addition to the increasing use of electric vehicles, autonomous (self-driving) vehicles (AVs) will contribute to opportunities for adaptive building reuse. It can be reasonably predicted that 50% of cars on the road will be autonomous by the year 2050 (Litman 2018). While AVs do not have an intrinsic carbon reduction like EVs, their carbon impact is through the opportunity presented by adaptive building reuse. Autonomous vehicles reduce the demand for traditional parking stalls, and therefore reduce the demand for parking garage space in existing structures, which equates to a sunk embodied carbon cost that is unfortunately underutilized without creative reuse of those parking structures (Brown 2012). Autonomous vehicles—whether personally-owned or operated by rideshare—can be continuously productive (Holloway 2018). With the future adoption of AVs, cars will no longer sit idle in parking garages, something they currently do at least 90% of the time (Lee 2014). A conservative assumption can be inferred that a 50% autonomous fleet is directly

Figure 1. Conceptual Visualization of Repurposed Parking Garages In Commercial Buildings. Image by authors.

related to a similar 50% reduction in parking garage demand. Accelerated AV adoption or sudden changes in transportation systems could result in an even more dramatic impact.

Notably, compared to peer American cities, Seattle has a particularly high number of vehicle parking stalls in garage structures (Scharnhorst 2018, Gutman 2018). Much of this parking is not in standalone garage structures, but incorporated within mixed-use commercial and multifamily buildings. With the aforementioned prediction of reduced demand for parking stalls lies a paradox: these commercial buildings represent the "highest and best" use for urban parcels, but half of their below-grade garage would no longer be productive. One solution proposed for underutilized parking garages is to repurpose them to facilitate urban food production (Szopińska-Mularz et al. 2018, Garfield 2017). The CCLS's research has shown that indoor farming has become economically feasible over the last eight years, primarily due to the availability of affordable and efficient LED lighting (Proksch 2017).

Many of the indoor farms studied as precedents for this applied use case are housed in existing warehouses. *Growing Underground* is an outstanding example of an operation installed in abandoned tunnels of the London Tube, and therefore most relevant to the limited volumes of space presented in this typology of adaptive reuse of parking garages, commonly constructed with ten feet clear height or less (Proksch 2017). Indoor farming operations can be combined with aquaponic systems. Aquaponics is the circular co-production of fish and plants in which fish waste provides nutrients for plant growth, while plants help clean water for the fish (Goddek et al. 2019). As a combination of land-based recirculating aquaculture and hydroponics, aquaponics can be a successful and highly resource-efficient means of urban food production.

RESEARCH FRAMEWORK

To assess the relative carbon impacts of the three critical topics that shape this adaptive typology, the study time period was carefully considered to isolate carbon impacts over thirty years, from 2020 to 2050. This time frame was selected to contextualize the net carbon impacts and align with carbon goals at local and international scales ("Seattle Climate Action Plan," UNFCC). The thirty years between the years 2020 and 2050 have been identified as a critical time frame when embodied carbon impacts outweigh lifecycle operational carbon impacts of new construction, in a concept known as the "time value of carbon" (Architecture 2030, King 2017).

The design application test cases allowed the research team to analyze the feasibility of repurposing underground parking garage space for the productive purpose of urban aquaponics. The buildings identified as appropriate test cases are mid-rise, mixed-use office buildings with at least two below-grade parking levels. The primary test case building was the Terry Thomas building with four above-grade levels of office and two below-grade levels of parking completed in 2008. The investigation identified three patterns of climate impact,measured in carbon dioxide equivalent, or CO_2e (Figure 2). The transition to electric vehicles is best expressed by a measure of avoided emissions, the operational carbon efficiencies over time using an electric vehicle compared to a gas powered vehicle. As opposed to operational emissions, the embodied carbon associated with the construction of the parking garage levels of buildings was emitted before the study period and represents a "spent" carbon cost, made more worthwhile and sustainably efficient the longer the space is utilized and operated for a suited purpose. The operational carbon footprint for aquaponic food production for this typology and setting is an absorbed CO_2e value over the 30-year study period of urban farm operation (Seattle City Light). While this time scale is shorter than carbon sequestration within a forest, the system behaves in a similar carbon neutral or carbon net-negative manner as opposed to a net positive emission (Lorenz 2010).

The scale of carbon impact is the final consideration of the research framework for indoor aquaponics as an adaptive reuse of parking garages. The three types of relative carbon impacts were first compared at the building scale. These impacts were then assessed at the city scale in order to gauge the magnitude of potential impacts if other existing buildings were to pursue the same adaptive reuse solution.

METHODS & CALCULATIONS

This study relies on a unique collaboration between the CCLS research lab and the professional design firm Weber Thompson to address the application of research ideas into real world scenarios. The research process began with the authors—architecture practitioners and academic researchers—drawing from their respective spheres of knowledge to identify the three primary topics intersecting at the proposed research problem: changing transportation trends, the adaptive reuse of existing buildings, and food production in cities via building-integrated agriculture. To narrow the

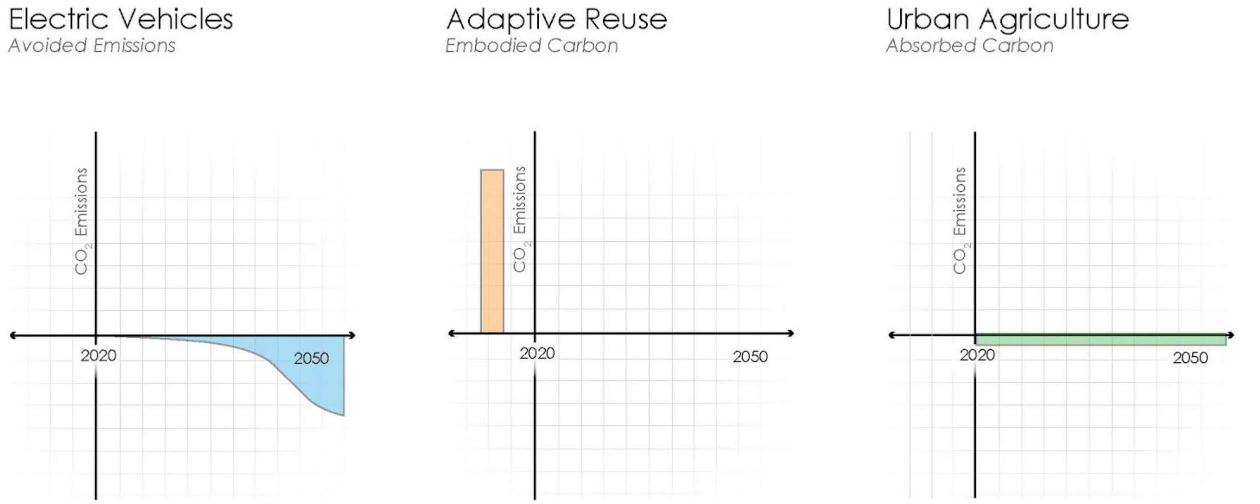

Figure 2. Carbon Impact Type Comparisons: Avoided Emissions from EVs, Embodied Carbon in existing construction, and Absorbed Carbon from an indoor growing operation. Image by authors.

scope of study, building case studies drawn from professional practice and aquaponics case studies drawn from academic research were used to establish assumptions and the design application for a below-grade parking garage retrofit with an aquaponics operation.

Built commercial projects from Weber Thompson's design portfolio provided the conceptual test cases for application (Weber Thompson). Urban hydroponics and aquaponics case studies from the CCLS's research (Proksch 2017) provided an idealized growing system specification and expectations for agricultural inputs and yields. As the growing systems were applied to the case study buildings, discoveries and constraints informed the assumptions and design applications in an iterative fashion.The desired result of this collaboration is that conclusions from the study reciprocally impact the spheres of professional practice and academic research by informing real world design opportunities and identifying future topics of study.

The carbon emissions avoided from use of electric vehicles was established using an analysis of a 2018 report on the manufacture of EVs by the International Council on Clean Transportation (Hall and Lutsey 2018, Carbon Brief 2019). The citywide carbon impact of electric vehicles in Seattle was established via data from a Greenhouse Gas Emissions Inventory published by the Seattle Office of Sustainability & Environment in 2016 (Seattle City Light). The building-scale carbon impact of electric vehicles in the Terry Thomas case study application was based on the actual layout of the parking garage. It estimates the number of vehicles transitioning from fossil fuel-burning to electric power at a scale comparable to the aquaponics adaptive reuse intervention — roughly 50% of the footprint of the total parking area. The embodied carbon impact of the existing Terry Thomas below-grade parking garage construction was estimated using a Construction Carbon Calculator. Designed to help "developers, builders, architects and land planners approximate the net embodied carbon of a project's structures and site," the tool provides a rough estimate, "accurate within 25%, plus or minus" (BuildCarbonNeutral).

The calculation method for urban food production (leafy plants and fish yield) involved several iterative steps. The system selection, layout, growing area to tank volume ratio, and yield were based on the most applicable operational case studies available from literature (Proksch 2017). Using these inputs, the capacity for the hydroponics and aquaculture components was quantified and critical information established for plan layouts. The conceptual system layout was applied to the geometry of the repurposed parking garage and adjusted via design iteration and testing.

The energy demand for urban food production is an important consideration and calculation. While a controlled growing environment can have advantages over conventional outdoor agriculture in productivity and resilience, indoor growing requires energy-intensive lighting to replace natural sunlight (Zhang et al. 2018). The LED lighting energy therefore comprises most of the operational energy demand of an indoor urban farm. Additional energy demand may be a result of additional ventilation required for the underground operation; however, parking garages are already designed for significant ventilation per mechanical codes. In order to scale up these impacts from the building to the city, publicly available data sets from the City of Seattle Open Data portal were used (Seattle 2020). The gross area of commercial office buildings similar to the test cases and the gross area of structured parking in commercial office buildings in Seattle were isolated.

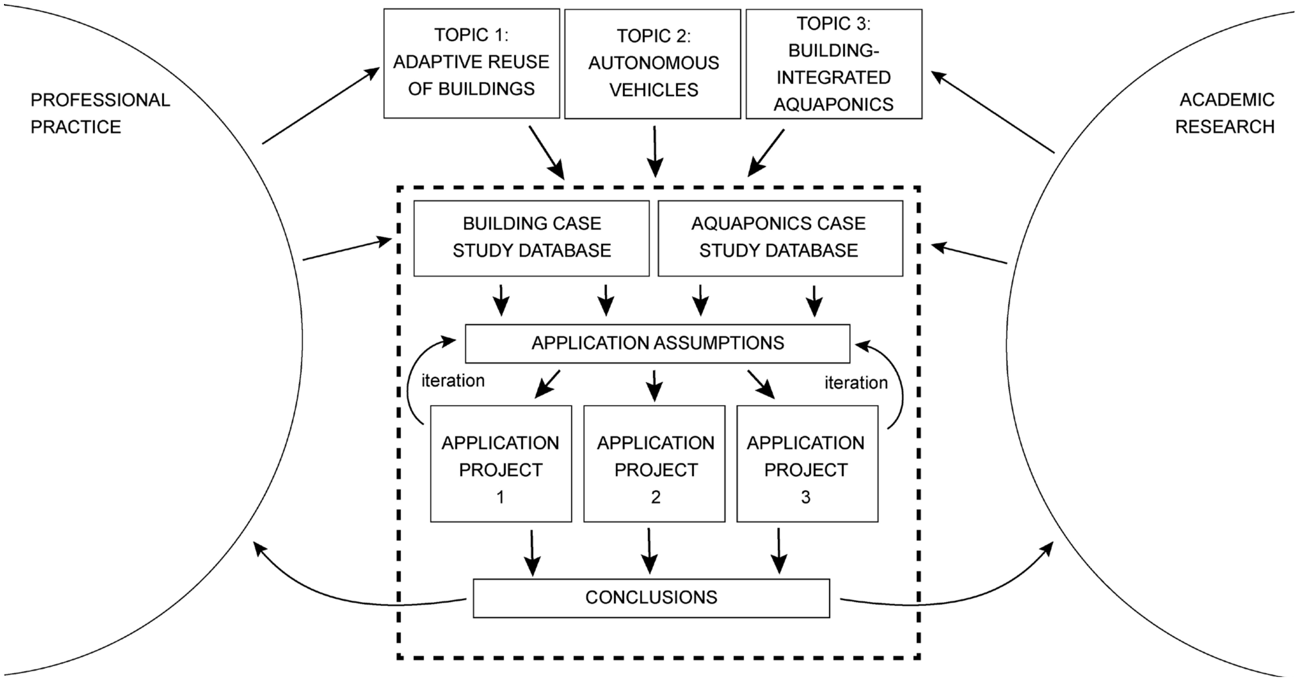

Figure 3. Model for Transdisciplinary Academic/Professional Collaboration. Image by authors.

RESULTS

To evaluate and compare the three types of carbon impacts in the case study application, the first result is the impact of the transition to EVs. This is an anticipated transition based on a changing EV market and availability, with no design intervention required. The 33 vehicle stalls in the lower level of the case study parking garage—the same study area for the conceptual adaptive reuse—correlate to 33 vehicles transitioning from conventional combustion to electric vehicles, representing a carbon savings of approximately 545.5 tons CO_2e. The rate of CO2e reduction between conventional and electrical vehicles is a rough approximation from the comparison of greenhouse gas emissions in the 2018 briefing referenced above (Hall and Lutsey 2018, Carbon Brief 2019). This is based on a new Nissan Leaf EV assuming 150,000 km driven over a 12-year lifetime. This finding from Hall and Lutsey is independent from the source of electricity in carbon-neutral Seattle, and for the purpose of this study assumes a more common regional electric utility carbon footprint for more widespread applicability.

(Carbon Emission Difference from Conventional Vehicle to EV / km) x (Vehicle Lifetime km) = (Carbon Emission Reduction per Vehicle)

((200 grams -100 grams) / km) x (150,000 km) = 15,000,000 grams CO_2e reduced per vehicle

15,000,000 grams CO_2e reduced ÷ 907,185 US tons/gram = 16.53 tons CO_2e reduced per vehicle

33 vehicles x 16.53 tons CO_2e reduced per vehicle = **545.5 tons CO_2e reduced**

Next, the impact of the transition to AVs in the case study application was evaluated. Based on the estimated 50% reduced parking demand (equivalent to one below-grade parking level), in the projected future state, 13,350 square feet of below-grade concrete construction would no longer be productive. This is non-occupiable space with no windows, no thermal envelope, and minimal waterproofing. The building already has sufficient occupant and building storage, so opportunities for a building owner or landlord to lease and monetize this newly acquired building area are limited. This area represents a sunk carbon cost embodied in that construction.The embodied carbon emissions in this construction were evaluated using a Construction Carbon Calculator (BuildCarbonNeutral). The resulting net embodied CO_2e for this project is approximately **606.3 tons embodied CO_2e.**

Finally, the carbon impacts of urban food production were determined. Insights from Project CITYFOOD (Proksch and Baganz 2020) informed the aquaponic growing system configurations conceptually applied to the Terry Thomas garage floor area. The nine-foot clear height in the existing parking garage accommodated three layers of stacked growing, providing nearly 10,000 square feet of growing area for hydroponics. The proper ratio of aquaculture tanks and equipment to the hydroponic beds was determined through case study analysis. Ingress and egress would be provided through a dedicated existing garage ramp accessed via public alley.

The carbon impact of the aquaponics operation has two aspects: carbon emissions through energy demand, and a carbon benefit from sequestration of the plants. Research from several simulation-based models suggests that a large

BUILDING CASE STUDIES

The Terry Thomas
225 Terry Ave N
4 stories office over 2 stories
subgrade parking
67 parking stalls
27,000 SF subgrade parking

DATA 1
744 N 34th Street
5 stories office/retail over 2 stories
subgrade parking
152 parking stalls
60,000 SF subgrade parking

Living Stone
3524 Stone Way N
5 stories office/retail over 2 stories
subgrade parking
149 parking stalls
72,000 SF subgrade parking

VERTICAL INDOOR FARMING

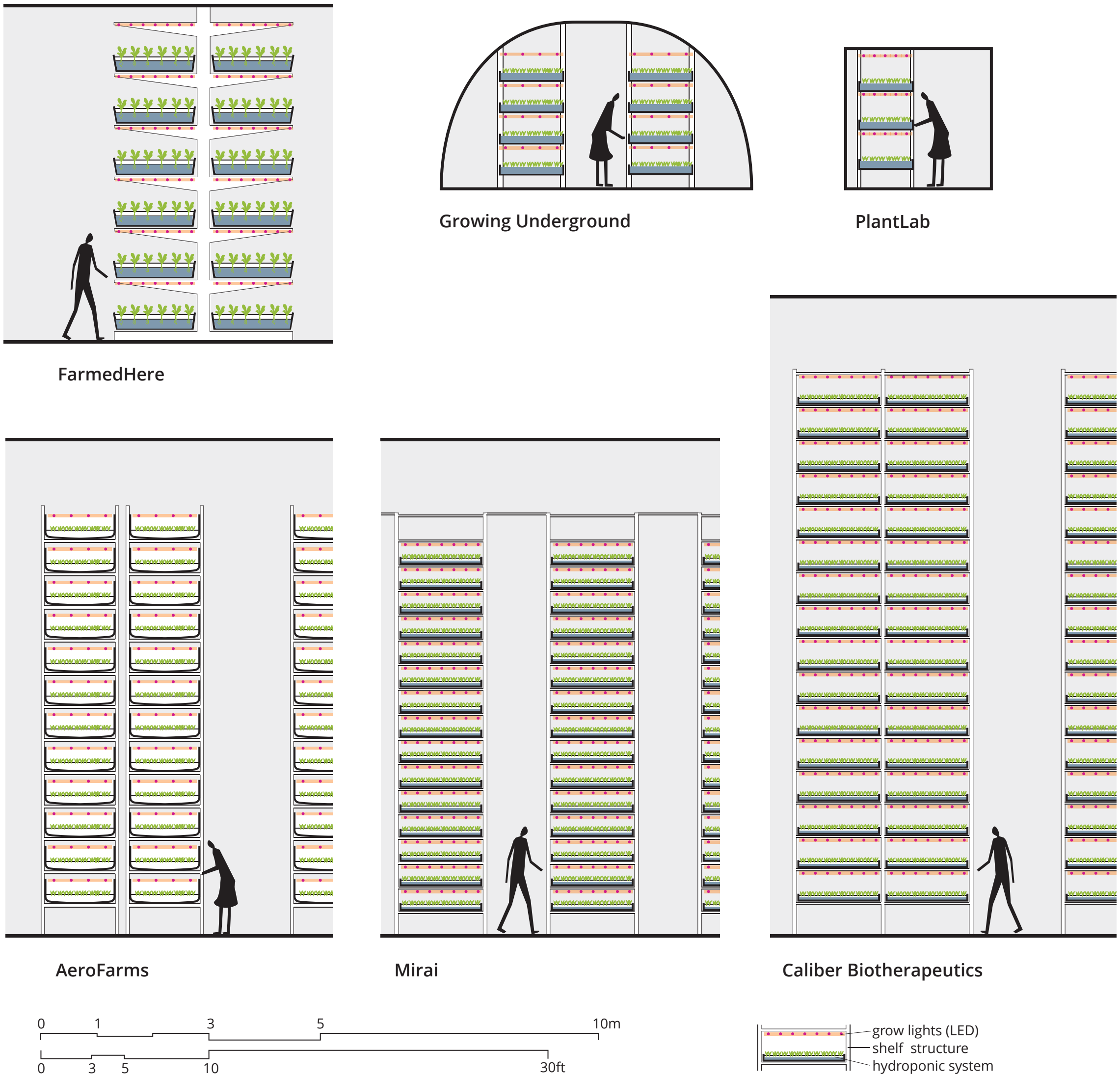

Figure 4. Two Sets of Case Studies: Office Buildings by Weber Thompson in Seattle and Case Studies of Hydroponic and Aquaponic Indoor Farms. Proksch, Gundula. Creating Urban Agricultural Systems: An Integrated Approach to Design, Routledge 2017.

portion (more than 95%) of the electrical demand for windowless indoor farming operations comes from the lighting required for plant production (Benis et al. 2017). For the scale of this research, all other contributions to the energy demand for the farm were considered negligible (Graamans et al. 2018). An estimation of the energy consumption for the hypothetical indoor farms would therefore largely depend on the lighting specifications including photosynthetic photon flux density (PPFD) and photoperiod. PPFD values measure the amount of photosynthesis-inducing photons that reach the plant surface over a given growing area (Fluence). Photoperiod, the amount of time per day that a plant receives these photons, and PPFD values depend on the crop selection, as different plants require different photon amounts for a healthy photosynthesis process. To simplify the calculations, lettuce was the assumed crop selection for all growing trays in the farm. This allowed for a uniform set of lighting specifications across the entire growing system.

In a thorough study of optimum lighting conditions for lettuce production in an indoor farm, the PPFD values were 250 μmol/m2/s and a photoperiod of 16 hours/day (Zhang et al 2018). With the established PPFD and photoperiod values, an in-depth assessment of possible LED light fixtures was conducted. LED light fixtures were selected (as opposed to other lighting options such as heat lamps) for maximum energy efficiency. This assessment identified LED lighting fixtures offering PPFD values in the recommended range from a variety of lighting manufacturers. Using the lighting fixture manufacturer specifications and the assumed conditions of the hypothetical growing operation, the energy demand for the farms was estimated at 65-70 kWh/year/sf of growing space. In the Terry Thomas case study, the high end of this range generates a lighting energy demand of 675,150 kWh/year.

(Energy Density) x (Growing Area) = (Total Energy Demand)

(70 kWh/year/sf) x (9,645 sf) = **675,150 kWh/year**

This electric demand from lighting would create significant carbon emissions in many geographic settings. In this case, Seattle's carbon neutral grid translates to net zero operational carbon emissions (Seattle City Light). Were the case study application not located in the Pacific Northwest, the theoretical emissions of this operation would be approximately 231.5 tons CO_2e/year.

For the growing area of 9,645 square feet, the annual yield was estimated (from case study data) to be 128,600 lbs of leafy greens. While green lettuce was the assumed crop for estimating lighting demand, leafy greens could also include red romaine, red kale, rainbow chard, arugula, bok choy, swiss chard, tatsoi, green kale, beet greens, and green romaine. Through photosynthesis, the leafy greens will absorb an estimated 6 tons of CO_2 per year (Mota et al. 2010). This carbon is only temporarily sequestered until the leafy greens are consumed. At this rate over 30 years, the aquaponic food production in the adapted space would absorb 180 tons of CO_2. This is an added benefit to significant protein and vegetable crop yields.

(Growing Area) x (Yield Ratio) = (Annual Plant Yield)

(9,645 sf) x (13.33 lbs/sf) = **128,600 lbs/year leafy greens**

(Annual Plant Yield) x (Average Plant Weight) x (Carbon Sequestration) = (Annual Carbon Sequestration)

(128,600 lbs/year) x (1 plant / 2.15 lbs) x (0.2 lbs CO_2 / plant) = 11,963 lbs CO_2/year

11,963 lbs CO_2/year ÷ 2,000 lbs/ton = CO_2 / year

(6 tons CO_2 / year) x (30 years) = **180 tons CO_2 sequestered**

Scaling up the proposed building case study to citywide impacts, a publicly available Seattle dataset was used to estimate the number of similar commercial office buildings within city limits, as well as parking areas within commercial office buildings (Seattle 2020).

(Case Study Parking Area) x (Scale-Up Factor) = (Citywide Parking Area)

(13,350 sf) x (Scale-Up Factor) = (16,153,500 sf)

Scale Up Factor = **1,210**

A citywide transition to EVs would therefore reduce over 660,000 tons of carbon dioxide emissions:

(Case Study EV Carbon Reduction) x (Scale-Up Factor) = (Citywide EV Carbon Reduction)

(545.5 tons CO_2e reduced) x (1,210) = **660,055 tons CO_2e reduced**

A citywide adaptive reuse of parking garages from the future transition to AVs leverages over 730,000 tons of preexisting embodied carbon in construction:

(Case Study Embodied Carbon) x (Scale-Up Factor) = (Citywide Embodied Carbon)

(606.3 tons embodied CO2e) x (1,210) = **733,623 tons CO2e embodied**

A citywide application of urban food production through indoor aquaponics in parking garage retrofits would temporarily offset nearly 220,000 tons of carbon dioxide:

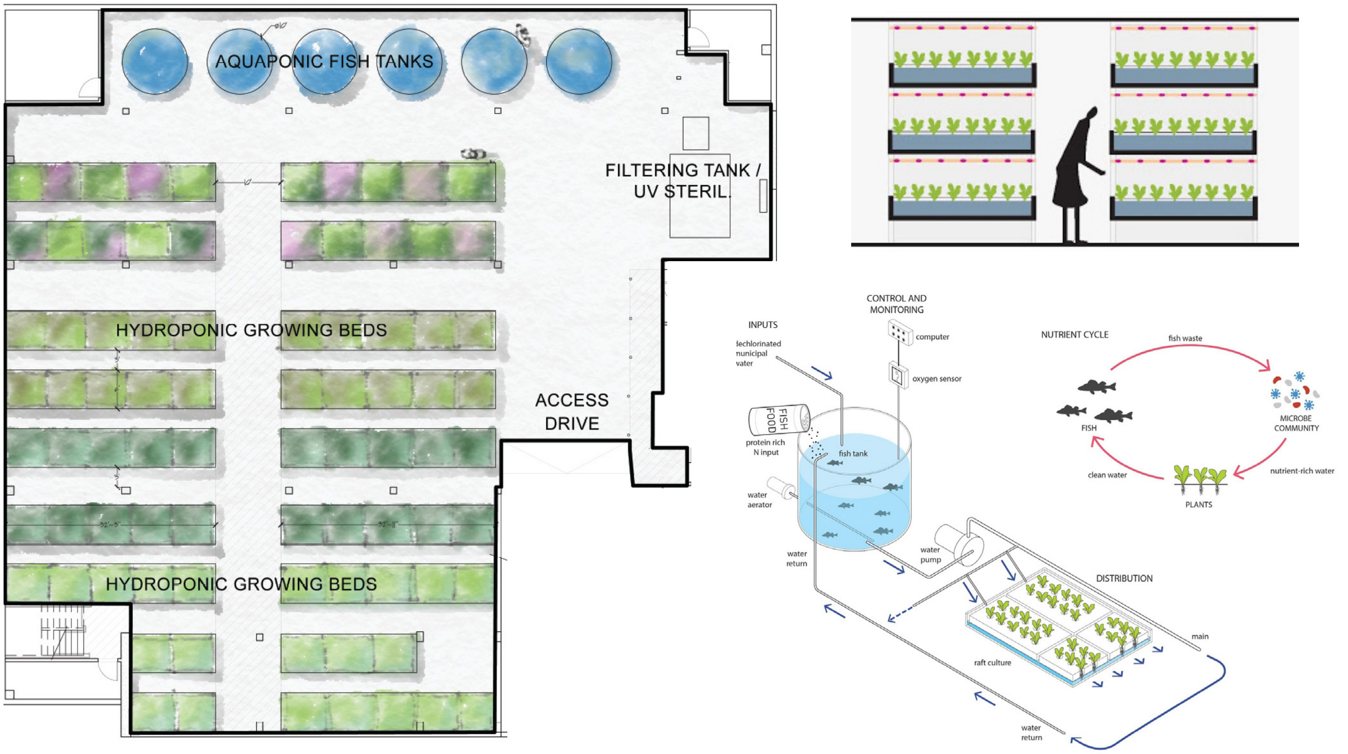

Figure 5. Illustrated plan and section of the Terry Thomas case study aquaponic growing operation. Image by authors. Aquaponics Growing System Diagram. Proksch, Gundula. Creating Urban Agricultural Systems: An Integrated Approach to Design, Routledge 2017.

(Case Study Carbon Sequestration) x (Scale-Up Factor) = (Citywide Carbon Sequestration)

(180 tons CO2 sequestered) x (1,210) = **217,800 tons CO2e sequestered**

DISCUSSION & CONCLUSION

These preliminary results suggest that in Seattle, and other regions with current and future carbon-neutral electricity grids, the reuse of underground parking garages for indoor aquaponic growing may be a favorable and opportunistic adaptive reuse strategy. While leafy greens are the most commonly used in indoor hydroponic and aquaponic operations, and therefore appropriate for this study, the cultivation of low-light crops such as endives and mushrooms might further reduce the energy demand for grow lights and their associated carbon footprint.

Though some building-integrated agriculture solutions (such as rooftop greenhouses) can offset energy costs with natural sunlight, this study was limited to the reuse of underground parking for several reasons. This underground parking area is difficult to imagine as productive in a future low-demand scenario. Additionally, the case study application as designed limits the impacts to commercial office buildings above. This is why the research team did not explore skylights or other methods for introducing daylight into the space that would impact the upper levels. Most importantly, the LED artificial lighting scheme is the most economically feasible and scalable indoor growing solution. It can be applied universally in all seasons, weather, and geographic locations.

To build on this study, a more detailed analysis would include additional energy demands for the aquaponics operations (noted above as negligible compared to the lighting demand). These demands include mechanical ventilation, pumps and tank equipment, water needs, and other inputs for the aquaponics operation. An additional aspect of this intervention that was not studied is the distance between food production and consumption, also known as “food miles,” (Engelhaupt 2008) and their net effect on CO_2e reduction. While intuitively this seems to be a carbon (and social) benefit to the building-integrated solution presented, the literature on this topic was not conclusive. Further, it is difficult to establish a baseline, i.e. pinpoint where consumers of leafy greens and fish get their food from typically, and thus difficult to make a direct comparison.The purpose of urban agriculture is often to supplement traditional farming, not replace it. Conventional rural crop growing, with its vast scale of operation, low land costs, and subsidies, is expected to remain the most economical for the foreseeable future. While food miles were not addressed, if studied, the EV impact to food miles in transport would need to be considered when comparing an urban farming operation to a more traditional rural farm.

For more granular data, additional commercial building case studies could be studied to yield basic rules about the most common layouts and limitations. Multifamily buildings with parking garages are also prevalent in Seattle, and would pose a similar paradox in a near future with AVs as a substantial portion of vehicles on the road. Therefore multifamily buildings could be included in the data, while acknowledging that residential garages often have different layouts from commercial garages (smaller stalls and aisles, tandem parking, additional tenant storage associated with stalls, etc.)

Economic impacts were not studied extensively in this project; however costs, revenues, and profits could be estimated for the proposed hypothetical aquaponics operation. These could be compared to the income commonly generated from commercial parking stalls (that would no longer be productive in the anticipated future scenario) with the option to plan for a phased implementation.

If predictions are correct, the 600 tons of carbon embodied in half of the existing parking garage will go to waste without a creative adaptive reuse strategy. Parking garages in commercial buildings are an extreme example, however not the only building type that may suffer the fate of future underuse. The notion of "sunk carbon cost"—that embodied carbon in existing buildings should be accounted for, preserved, and adapted—informs a philosophy of sustainable construction and global carbon mitigation (Preservation Green Lab 2016). The embodied carbon estimates stated herein could be confirmed using Athena Impact Estimator for Buildings, Tally, EC3, and other robust tools for estimating embodied carbon in construction.

In studying the impact from building case study scale to larger scales, a more comprehensive and granular building database could be used to identify structures in Seattle where this intervention would be most relevant. Finally, data sets for larger geographic areas could be used to estimate the potential impact of this type of intervention at state, regional, national, and international scales.

Based on relative carbon impact, the aquaponics adaptations of parking garages do not seem to be a primary strategy for reducing global carbon emissions. There are many strategies that will be more effective at this, and should be the focus of organizations and individuals with a primary focus on preventing and mitigating climate change (Project Drawdown). Instead, the key takeaway of this study is acknowledging the opportunity for a unique and beneficial adaptive reuse strategy, the quantification of the relative carbon impacts, and the responsible minimization of the resulting impacts through efficient lighting and a low-carbon electrical grid.

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