Building an Ecosystem: Integrating Rooftop Aquaponics with a Brewery to Advance the Circular Economy

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By 2050, two-thirds of the world's population will live in cities and consume 80% of the global food supply. As the changing climate exacerbates pressure on all sectors of the economy, new frameworks for resource management in urban areas have been introduced. The food-water-energy nexus and the circular economy are two prominent examples; these conceptual frameworks recognize that resources consumed by cities are finite and intricately interdependent. In alignment with these ideas, professionals in the built environments shoulder a significant responsibility to design future buildings, neighborhoods, and cities that can sustain themselves while exerting minimal impact on the surrounding environment. The supply and consumption of food, water, and energy in future cities have, therefore become an architectural problem - and an opportunity for designers to contribute to a more significant societal shift.

As cities transform to manage the food-water-energy nexus sustainably, architectural design that is intimately involved with the industrial processes that buildings host can play a crucial role in closing the urban resource loop. Urban agriculture projects, such as aquaponics, that depend on technological innovation and an ecosystem approach are becoming more common. In the interest of achieving a fully circular urban economy, aquaponic farms' inputs and outputs can be integrated with those of other urban facilities. Through literature and case study review, this paper investigates the potential integration of aquaponic greenhouses with brewery spaces to make use of the circular nature of this growing system. Potential resources that can be linked between integrated greenhouse aquaponic growing and brewing include water, heat and energy, and organic matter. Careful design and a wide range of innovative technologies can be used to recycle growing and brewing process byproducts and reduce the overall energy and water demand while producing fish, crops, and beer.

INTRODUCTION

Creating resilient built environments which can increasingly adapt to and mitigate environmental wicked problems within the reality of anthropogenic Global Climate Change forms a heightened imperative for designers and built environment professionals of today, and of the future. Ambitious, ongoing innovation by the design community to help address proliferating environmental challenges which impact human health, natural systems, and planetary survival cannot be just an ideal, but must become a realized priority. Meaningfully enterprising design and construction should seek not only to bolster the resilience of the built environment itself, but to strive to synergistically support the success and resilience of other vital resources and systems including food, water, and energy, while also protecting and fostering human and environmental health, safety, and wellbeing.

This endeavor will require increasing buy-in to optimization and synergetic thinking about our built environments, and impels transdisciplinary coordination across specialties, sectors, research, and application. Developing new lines of thinking and innovation around integrated building systems and new typologies in the built environment will be vital. Buildings make-up about half of the world's primary energy consumption, while food production and agriculture consume another 13 to 15% in developed countries (Nadal et al. 2017). As the changing climate exacerbates pressure on all sectors of the economy, new frameworks for resource management in urban areas have been introduced. The food-water-energy nexus and the circular economy are two prominent examples; these conceptual frameworks recognize that resources consumed by cities are finite and intricately interdependent. Resource-efficient food production systems such as aquaponics, and their integration with other energy intensive industrial food processes such as breweries, can be an effective sustainable direction for building integration consideration and innovative design. This paper will preliminarily explore the potential of one such hypothetical typology which seeks to redefine the intersection of our built environment with that of our food systems by introducing the concept of the Brewery Integrated Aquaponics Farm.

Breweries face some of the same environmental issues that aquaponic operations seek to solve, including water consumption and waste, by-product waste, and high energy use (Olajire 2012). The impacts of this are not negligible, beer is among the top five consumed beverages in the world, and is produced on global scales reflecting its popularity (Olajire 2012). A multibillion dollar industry, brewing is an important

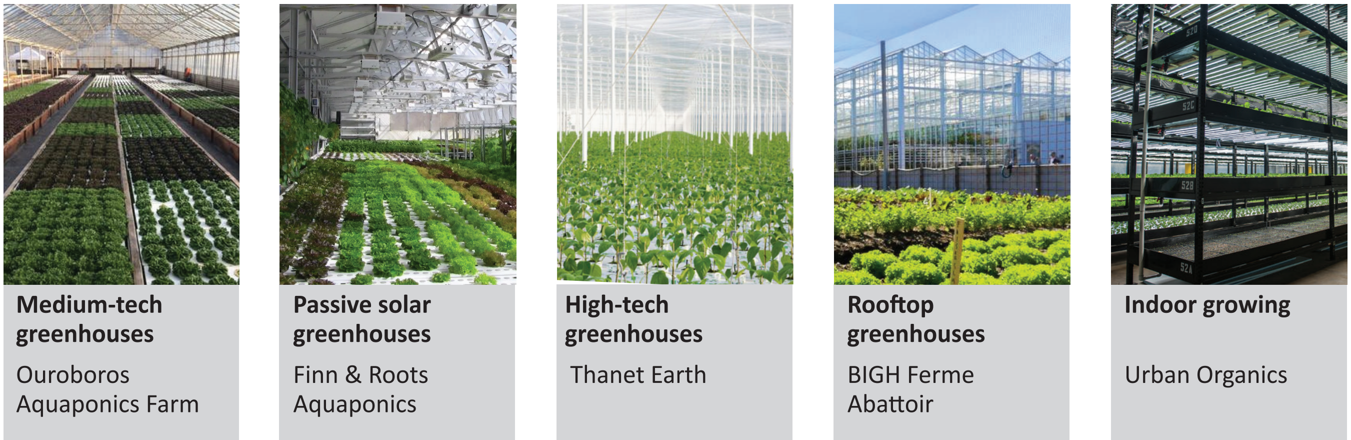


Figure 1: Typologies of Controlled Environment Agriculture (CEA).

economic sector which generates income, attracts tourism, and drives agricultural production of key ingredients, particularly grain (Olajire 2012). It is an energy and water intensive process in which malt extracts are blended with hops, sugar, and water, and fermented with yeast (Olajire 2012). Technical feasibility and economic practicality are some of the main restrictions on setting forth sustainable waste stream practices found in recent brewing studies, and thus advancement of these more efficient production scenarios has lagged (Weber and Stadlbauer 2017). Creating on-site sustainable food systems which are fully integrated with the building and aquaponic farm may pave a path to increasingly circular economies of brewing and food production, facilitating efficient and cost-saving synergies. Successful brewery-integrated aquaponics practice is likely to also benefit from supplemental income from agrotourism, potential restaurateur interest, and venue popularity.

For production and environmentally-oriented programs, industrial buildings offer an impactful scale, which is a factor in our selection of an aquaponic-brewery for this exploratory paper. Our investigation of this hybrid topology is motivated both by its intriguing multi-modal promise as a successful bio-circular building type and as an exercise in integrated design thinking which practices combining closed-loop principles with the incorporation of living systems in architecture towards the development of environmentally sustainable future cities.

AQUAPONICS, CONTROLLED ENVIRONMENT AGRICULTURE, AND BUILDING INTEGRATION

Aquaponic systems are composed of coordinated aquaculture and hydroponic systems wherein fish waste generates nutrients for plants, which in turn help to filter water for the fish (Goddek et al. 2019). While initially popular with backyard hobbyists, these systems increasingly are operated at a scale of commercial food production where they can exist as either coupled or decoupled systems (Bernstein 2011, Goddek et al. 2019). Advantages of aquaponic production include water savings, energy efficiency, and waste and nutrient recycling-properties which have generated the recognition of aquaponics as a farming approach that can help curb detrimental environmental impacts of food production and address sustainable development goals (Goddek and Körner 2019, Kotzen and Appelbaum 2010).

Offering a space-efficient, sustainable alternative to traditional agricultural methods, commercial aquaponics operations have grown extensively within the last decade. As recently as 2017, EU Aquaponics Hub identified 50 aquaponics research centers and 45 commercial operations, and these numbers are only growing (EU Aquaponics Hub 2017). There are far more commercial farms than research labs in the United States (Proksch et al. 2019). Over 94% of these existing commercial-scale aquaponics operations in the US have begun operation since 2012, and there are currently over 142 active for-profit aquaponics farms in North America (Proksch et al. 2019). Controlled Environment Agriculture (CEA) enclosures of varying typologies (Figure 1) are used by most aquaponics farms (Benke and Tomkins 2017). The capability to control growing conditions of fish and plants in a protected and optimally mitigated built-setting not only bolsters food, water, and energy systems resilience, but can also be synergistically integrated with building systems and operations to provide context-specific resource efficiencies (Sanjuan-Delmás et al. 2018a, Proksch et al. 2019, Nadal et al. 2017). Building-integrated aquaponics BI(Aq) can provide benefits including optimized sustainable outcomes and cost savings while holistically addressing the necessary indoor environmental parameters required for all living occupants including humans (farmers), fish, and plants.

Function and design of aquaponics, like that of living buildings, builds on theories of systems integration, through which innovative pathways to more sustainable and healthy built environments and production can emerge (Forrest 2002). In this context, integration can be defined as the merging of separate, different elements into a new whole, which in doing so will change the elements themselves as they exhibit new behaviors.

Existing aquaponic farming enclosure typologies have been utilized with varying degrees of building systems integration. Integrated rooftop greenhouses (i-RTG), typically Venlo-style high-tech greenhouses, can particularly benefit from the resources provided by host buildings, including carbon dioxide (CO_2) and exhaust heat, which can increase farm operation

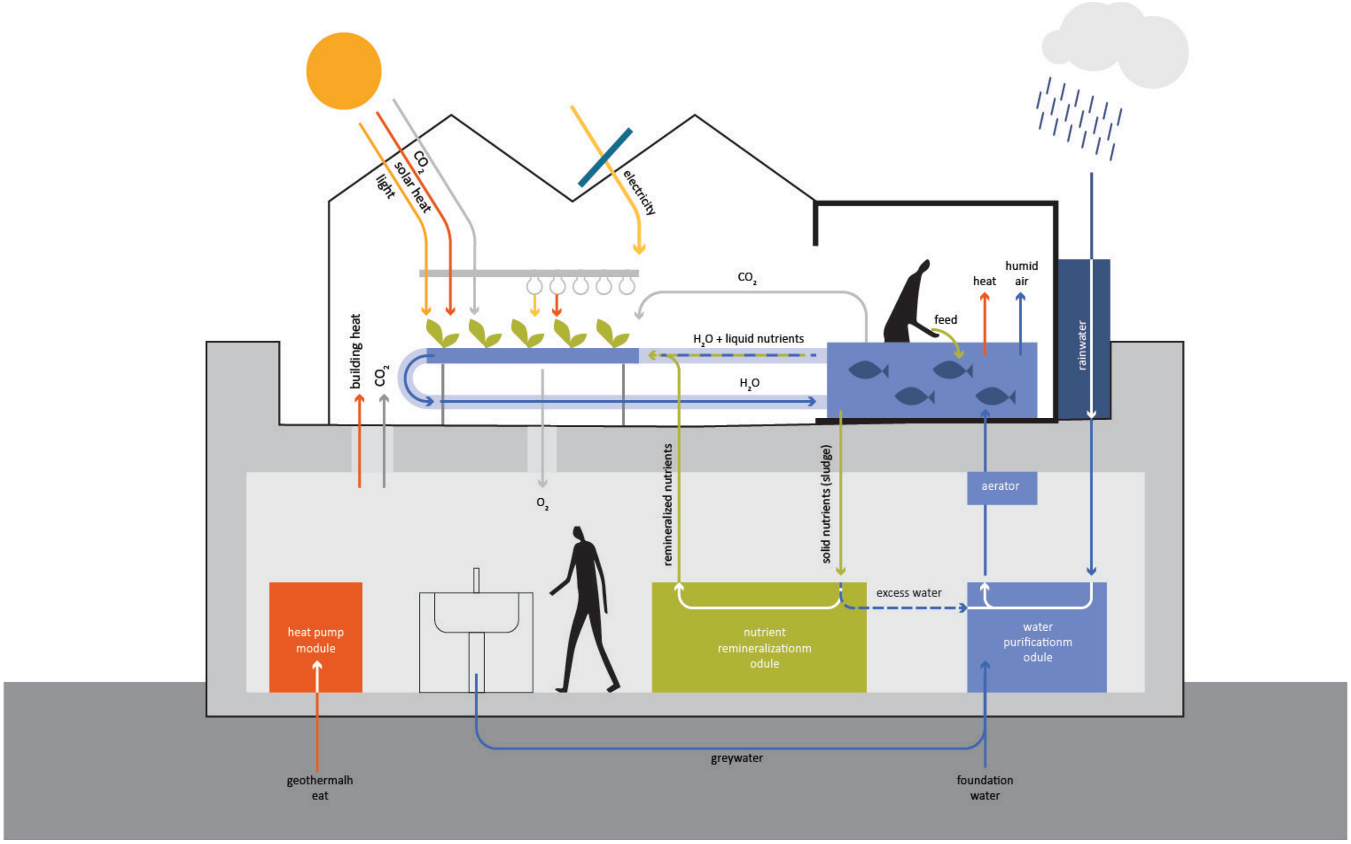


Figure 2: Building Integrated Rooftop Greenhouse with diagrammatic system integration (by authors).

feasibility while improving greenhouse and host-building performance in concert (Proksch et al. 2019). The broader concept of building integrated agriculture (BIA) has been described as a novel means of food production that establishes high-tech hydroponic systems inside of or on buildings using local and renewable energy and water (Gould and Caplow 2012). Notable ongoing study of BIA is conducted on the ICTA-ICP building at the Autònoma de Barcelona campus, a LEED-Gold certified research center building with integrated space for hydroponic vertical farming (Sanjuan-Delmás et al 2018a). Beyond hydroponic BIA alone, which requires external input of nutrients, BI(Aq) can foster a deeper synergetic potential by closing nutrient resource loops using fish waste generated and re-processed on-site (Skar et al. 2015).

The Food-Water-Energy nexus is a conceptualization framework of the interactions and exchanges of all three resources. Emerging from a global policy environment, it is increasingly applied to assess real resource flows and dynamics on the urban scale, and has the potential to provide impactful analytical and design outcomes at a building systems scale (Daigger et al. 2015). Within circular economies and cites, waste streams, or outputs traditionally seen as such, become the inputs for other processes. This type of approach harnesses intersections of the Food-Water-Energy nexus and can be seen in action in case studies such as that of The Plant in Chicago, a repurposed industrial building which houses several coordinated food production businesses, discussed below. Economies of scale would suggest that some of the most profitable food production scenarios, including in urban contexts, need to produce at sufficient magnitude to make a greater profit and outweigh production costs. This, along with the potential favorable structural character of traditional industrial warehouses for rooftop growing, suggest that building integration of aquaponics in industrial buildings and programs may be most promising for commercial success.

METHODS

As a preliminary assessment of an under-researched, emerging topic, this paper begins to synthesize and organize material which has not been previously comprehensively brought together in a systematic way. This work aims to build progress toward the creation of a methodological platform upon which to conduct future in-depth analyses which will quantitatively and qualitatively assess synergistic BI(Aq) potentials, performance, and impact. To do this in a context wherein availability of existing holistic data is limited, three main methods were used, these are: 1) Literature Review of aquaponics system and brewery system elements and operation requirements, 2) Case Study Review of existing BI(Aq) systems, and 3) Preliminary discussion of resource assessment methodologies which seeks to explore avenues to assess the comparative resource outputs and inputs between aquaponics and breweries. The literature review process was structured to reflect integration theory. Literature regarding different system elements, within aquaponics and brewery systems and buildings respectively were assessed separately. Per integration theory the conceptualization is that these system elements will ultimately be intersected into a new

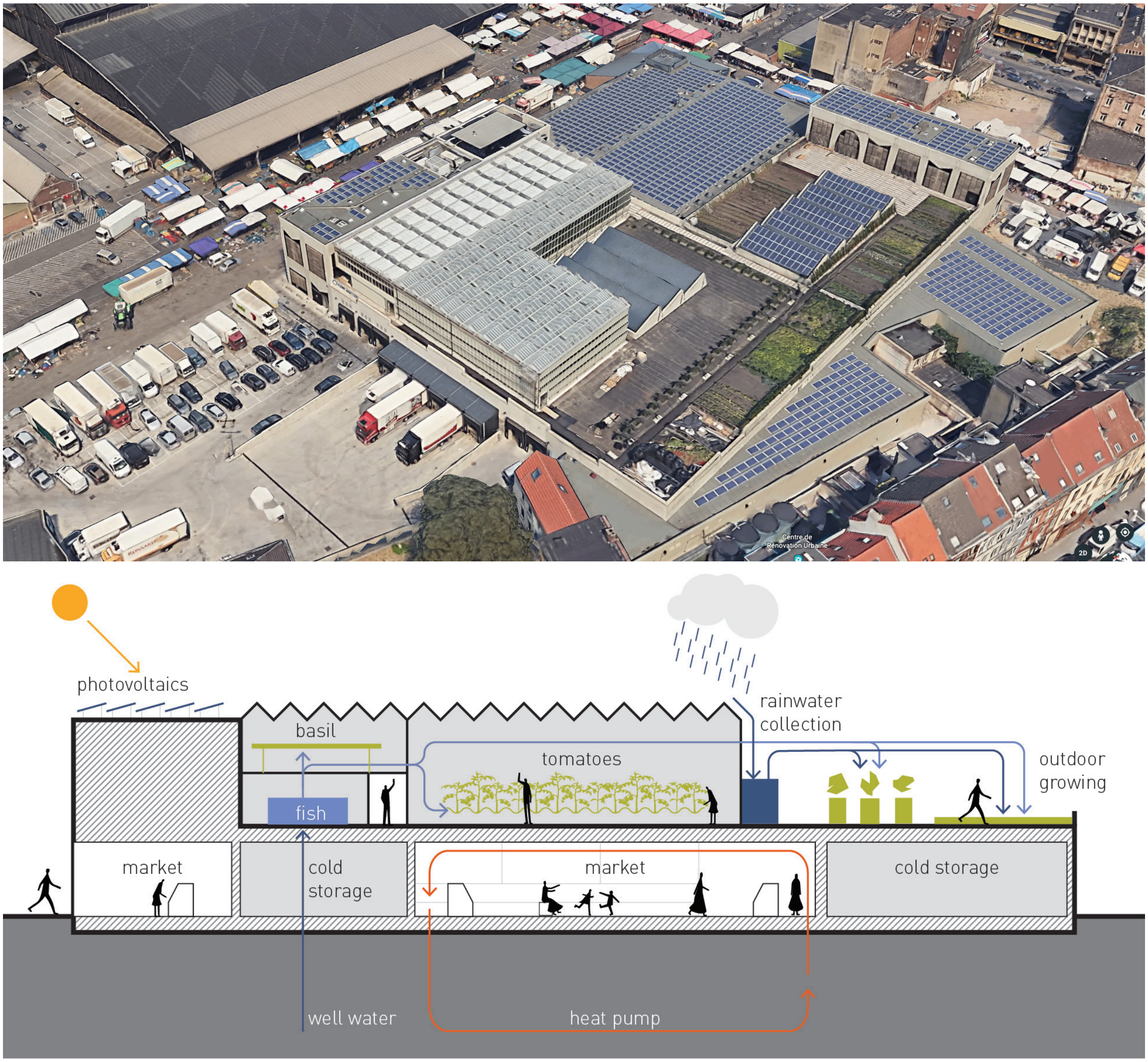


Figure 3. BIGH Ferme Abattoir in Brussels, Belgium, aerial view (google maps, top) and diagrammatic building section (by authors, bottom).

whole and exhibit new synergetic behaviors within the now holistic system (Van Dijk et al. 2014). Accordingly, interactions which could define these meeting and merging points were also reviewed, in the form of a literature review of potential technology and optimization synergies and known approaches to building-integrated agriculture (BIA). Case study review focused on two existing BI(Aq) systems: BIGH Ferme Abattoir, located in Brussels, Belgium, and The Plant, located in Chicago, Illinois, in the U.S. to document and assess the current state of the art for BI(Aq).

BIGH FERME ABATTOIR

BIGH's first urban farm is the Ferme Abattoir, which is built on the roof of the Foodmet market hall in the historical Abattoir (former slaughterhouse) site in the heart of Brussels, Belgium. BIGH operates its aquaponic production in a high-tech greenhouse and rents the rest of the roof to a non-profit outdoor soil-based farm, which uses the rooftop garden for educational programs. The operations of both farms are closely linked to the resource flows of the building systems. BIGH's aim is to create an integrated, circular, zero-waste production of fish, vegetables, and herbs.

BIGH (which stands for Building Integrated Greenhouse) was founded by the architect Steven Beckers, who has worked on circular economy projects in the real estate sector with his consultancy company Lateral Thinking Factory since 2011 (BIGH). For the development of the rooftop farm, BIGH collaborated with ORG architects located in Brussels and New York, as well as ECF Aquaponics Farm Systems, which runs an aquaponic greenhouse prototype in Berlin. The development of BIGH's Ferme Abattoir took about one year. Construction started in

2016, the outdoor gardens were in place in 2017 (currently 7,500 ft2, eventually 22,000 ft2), and the aquaponic farm with its 22,000 ft2 rooftop greenhouse started operation in 2018 (see Figure 3). After the construction of the first farm, the BIGH holding SCA, the developer and operator of the aquaponic urban farm, is interested in developing a network of urban aquaponics greenhouse farms in Belgium and abroad.

BIGH's Ferme Abattoir uses a heat pump to support the heating and cooling of the greenhouse needed to operate it year-round. The heat pump also supports the cooling of the cold storage in the market. Supplemental heating is provided by a gas heating that produces CO2, which is used for the CO2 fertilization of the greenhouse. The fish water of the decoupled aquaponic system is used to irrigate hydroponically grown tomatoes and herb plants grown on tidal tables, as well as the outdoor gardens. To minimize the use of municipal tap water, the farm uses filtered rainwater collected on the greenhouse roofs and local well water as additional water sources. PV arrays installed on the adjacent rooftops offset the electricity used for the supplemental LED lights in the greenhouse. Overall the Ferme Abattoir's fish farm can produce up to 39 US tons of striped bass per year. The fish is grown without any chemicals and antibiotics to protect the communities of microorganisms essential for the aquaponic systems. The rooftop greenhouse is operated with biological pest control and biological pollination with bumble bees. Likewise, within the greenhouse and outdoor gardens, no chemicals or pesticides are used.

THE PLANT

Located n Chicago's Back of the Yards neighborhood, The Plant is a food business incubator that aims to demonstrate sustainable food production and economic development by closing waste, resource, and energy loops. The Plant is the adaptive reuse of a 93,500-ft2 former meat packing facility that closed in 2006. The development company Bubbly Dynamics and its owner John Edel purchased the building in 2010 (Garcia 2019). Instead of stripping and taking down the building, Edel and his company made the best use of the existing USDA-grade facility and reusable materials in the redevelopment process (Proksch 2017). Currently, The Plant houses over a dozen small food businesses as tenants, including a bakery, kombucha and beer breweries, a coffee roaster, a cheese distributor, indoor and outdoor farms, and other emerging artisan food producers. In early 2019, The Plant's tenants generated a total of 85 full-time employee equivalent positions while using about 80% of the total rentable area. The Plant expects to complete construction and achieve full occupancy by 2020 (Bubbly Dynamics).

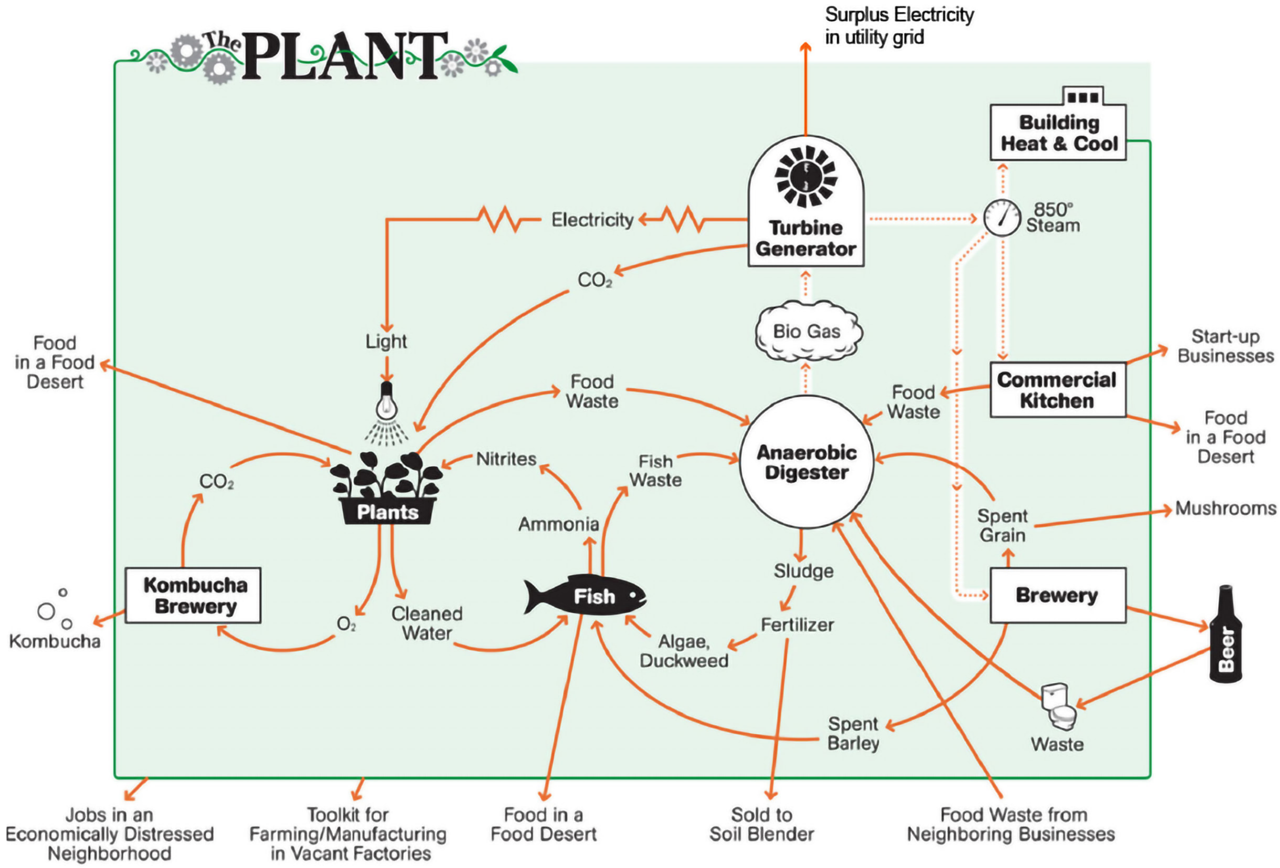
During the operation, one tenant's byproduct becomes a resource for another tenant. The transfer of resources within the building includes heat, electricity, CO2, oxygen (O2), water, nutrients, etc. When The Plant's build-out is complete, an anaerobic digester will be the key feature at The Plant. It will create all power, heat, cooling, and fertilizer needed by the operation by transforming organic waste into biogas and electricity (Figure 4). The organic waste produced by the tenants will be only a fraction of the organic waste that the anaerobic digester needs to run at full capacity. The large quantities of biomass will be sourced from resource and waste intensive food industries nearby. The Plant will demonstrate how food-production businesses can operate sustainably on the district scale by closing waste loops (Bubbly Dynamics).

Another integrated, closed resource loop is, for example, created by the aquaponics indoor labs. Fish water provides nutrients to the plants with the help of microorganisms. The plants produce surplus O2, which is beneficial in the aerobic Kombucha brewing process. In return, this process creates CO2, which can be fed back into the indoor grow spaces for CO2 fertilization. The anaerobic digester and generator create electricity for the grow lights as well as additional CO2 that might support the plant growth. The Plant's in house brewery benefits from the heat generated by the generator and anaerobic digester. The spent grain in the brewing process returns for the energy production into the anaerobic digester, while spent barley can be used as fish feed. The CO2 released in the brewing process might benefit plant production in the aquaponics system.

The indoor aquaponics farms are research and educational labs run by the nonprofit Plant Chicago, which supplements this research with investigations in algae bioreactors and sustainable fish feed to reduce the cost and environmental impact of feeding the fish in the aquaponics system. In addition to educating about various food production processes, Plant Chicago is committed to cultivating circular economies at the neighborhood level.

MATERIAL FLOW ANALYSIS (MFA)

Assessing the flows of resources within a system as they are utilized, changed, stored, or disposed of can be pursued by applying the laws of conservation of energy and mass through Material Flow Analysis (MFA). MFA provides an established approach of diagnosing system efficiency and productivity and of directing improvements where opportunities are identified to better link and integrate resource flows (Chance et al. 2018, Graedel et al. 1995). This approach was applied to The Plant in Chicago (Figure 4) allowing the assessment of material inputs, outputs, and food-water-energy use by all tenants. The study identified several opportunities to better synergize flows within the building and uncovered higher than expected resource wasting (Chance et al. 2018). Among the take-aways noted by the authors was the expected benefits of the flows of resources within a system as they are utilized, changed, stored, or disposed of can be pursued by applying the laws of conservation of energy and mass through Material Flow Analysis (MFA). MFA provides an established approach of diagnosing system efficiency and productivity, and of directing improvements where opportunities are identified to better link and integrate resource flows (Chance et al. 2018, Graedel et al. 1995).



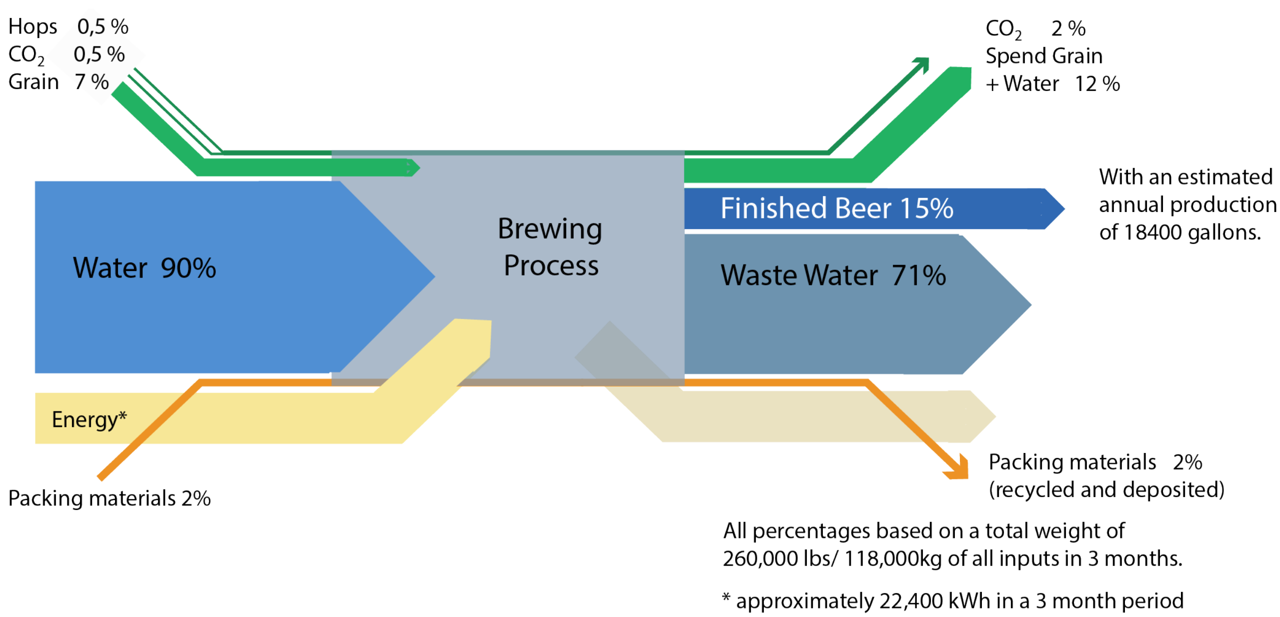


Figure 4: Closed Loop diagram of resource flows in The Plant (top). Original drawing by Matt Bergstrom. Brewery inputs and outputs based on Material Flow Analysis of Whiner Brewery by (Chance et al. 2018, Greene 2018). Diagram by authors.

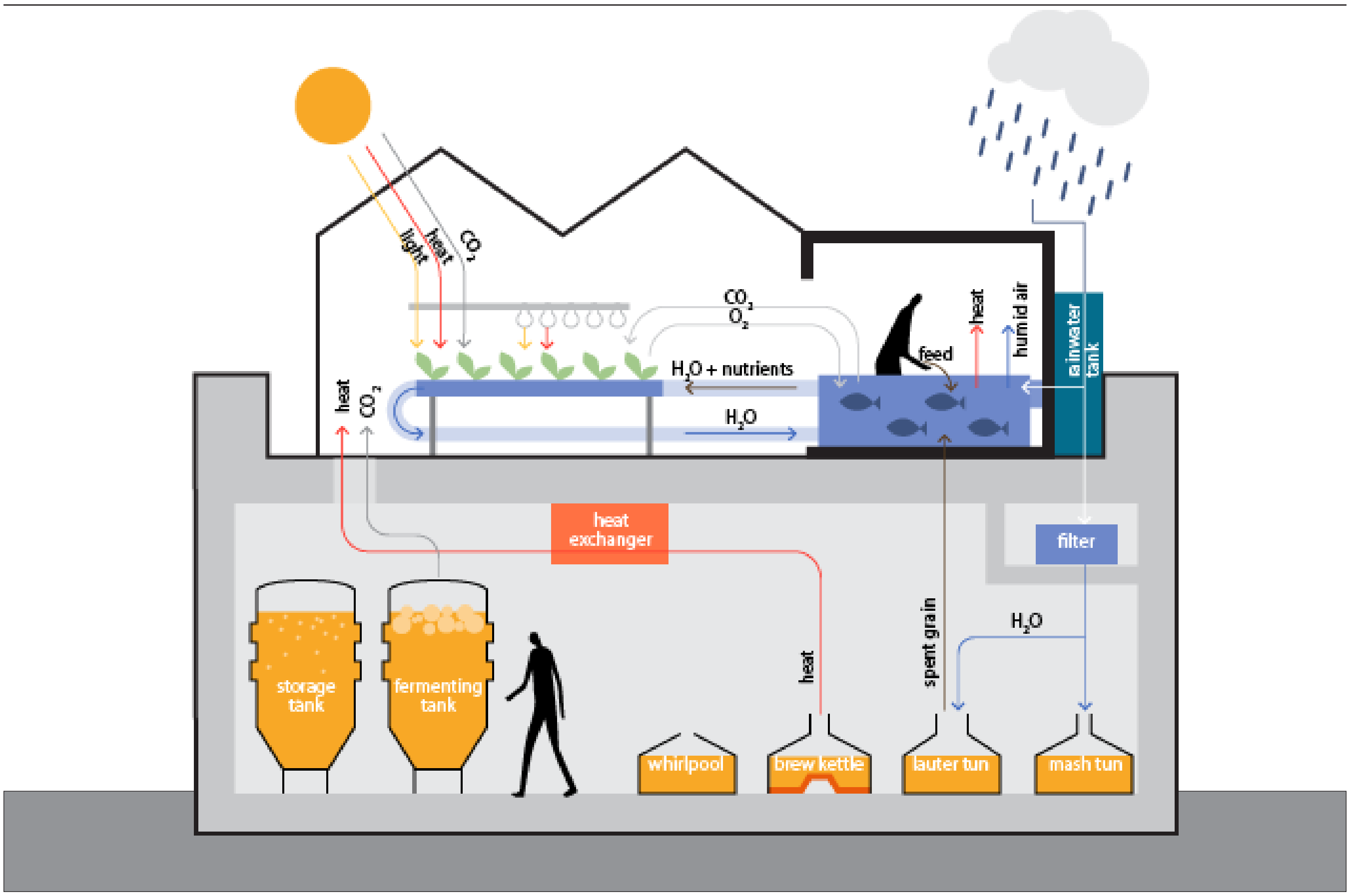


Figure 5: Aquaponic rooftop greenhouse and brewery systems combined; preliminary interaction diagram (by authors).

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PROTOTYPICAL BUILDING INTEGRATED AQUAPONIC BREWERY

A prototypical brewery-integrated rooftop aquaponics farm can harness and link-up resource flows that exist within both operational programs to contribute toward a functioning circular economy synergized through innovation of the built environment. Impacts of such a farm would sustainably approach the integration of all three linked components of the Food-Water-Energy nexus while facilitating an engaging, and demonstratively sustainable business model and venue, plausibly drawing a broad, multifaceted consumer base. Efficient resource use and reuse can form sustainable, profitable circular economic scenarios while additional income from the culinary tourism draw of a well-designed brewery with building integrated aquaponic food production could increase profit margin and commercial viability in urban settings.There are many synergistic potentials of building integrated aquaponics alone, and these become even greater when integrated with a brewery program (Table 1). Among them is the potential to recover and reuse CO2 from closed fermenters used in brewing and direct this toward greenhouses, which often use CO2 fertilization to bolster plant growth (Olajire 2012). Likewise, spent grain from brewing could be utilized as an ingredient in fish feed, closing one of the main open loops in current aquaponics practice (Kaur and Saxena 2004, Hassan et al. 2016). Integration of water treatment and reuse, and thermal exchange also provide potential routes for coordination toward optimized sustainable performance.

Quantitatively assessing potential resource flows in a BI(Aq) brewery system can make use of approaches such as MFA, as was applied to The Plant and Whiner Brewery, presented above. Whiner Brewery provides a good example of the resource usage of small scale breweries (Figure 4). MFA and other mass balance analysis approaches can track material and energy within a system of defined boundaries per the laws of conservation of energy and mass to account for linkages and transformation of these within a given system. While the specific values and exchanges can be expected to vary by brewery, aquaponic, and building system design and operation, MFA and mass balance can be used with application of understanding of

Table 1: Potential System Integration Strategies for Building-Integrated Aquaponic Breweries.

Nexus Component	Strategy	Integrated System impacts	References
Food	Food Production	Aquaponic operations have high food productivity and efficiency	Junge et al. 2017
	Nutrient Recycling	Aquaponic growth of produce closes nutrient cycle loops; -Prevents eutrophic effects of nutrient runoff	Proksch et al. 2019
	Sludge Digestion	Reuse of solid wastes, processed in bioreactors, helps maximize system efficiency	Goddek and Vermeulen 2018, Monsees et al. 2017
	CO_2 Exchange	Air exchange between buildings and greenhouses provide symbiotic CO2 and O2 flows;-Increases crop productivity and efficiency while reducing CO2 emitted by the building	Delor 2011, Sanjuan-Delmás et al. 2018b
	CO_2 recovery and reuse	Can source from closed fermenters and direct to greenhouse for improved plant growth outcomes	Olajire 2012
	Fish feed production	Spent grain and hops can be used as toward production of fish feed for aquaponic input	Sturm et al. 2012, Kaur and Saxena 2004, Hassan et al. 2016, Middendrop, 1995, Webster et al. 1991, Webster et al. 1992, William 1955
	Waste Biomass Co-digestion	Brewery and aquaponic wastes (including sludge) can be digested in concert toward different re-mineralized nutrient outputs and biogas production	Boneta et al. 2019, Sturm et al. 2012
	Hops Growth	Hops can be grown using nutrient rich water from fish feed and nutrient re-mineralization.	Tadevosyan et al. 2009
Water	Coordinated Reuse & Treatment	Rooftop building integration can minimize or eliminate the use of external water	Sanjuan-Delmás et al. 2018b
	Rainwater Capture	Increases water efficiency and mitigates stormwater overflow	Ackerman et al. 2013
	Foundation Drainage Water	Treatment and reuse of dewatering and sump water that would otherwise be sent to sewer as nuisance groundwater	San Francisco PUC Article 12C
	Coordinated water treatment	Breweries often require full advanced water treatment, this can be coordinated with that needed for aquaponic production and water can be reused within the system.	Simate 2015, Götz et al. 2014
Energy	Thermal Integration	Eliminates building solar gain and heat losses through roof and greenhouse heat loss through floor; -Captures waste heat from building exhaust air	Puri and Caplow 2009, Delor 2011, Sanjuan-Delmás et al. 2018a, Nadal et al. 2017
	Temperature regulation with Brewery	Greenhouse can coordinate thermal regulation with brewery; Hops grown on exterior walls can provide additional synergistic thermal and heat-island reducing effects.	Ercilla-Montserrat et al. 2017, Sturm et al. 2013, Mauthner et al. 2014, Sturm et al. 2012
	Evaporative Cooling	With rooftop greenhouse space can implement large evaporative cooling systems (would be otherwise unfeasible for buildings because of constraints including space, humidity-factors, and cost)	Caplow and Nelkin 2007
	Solar PV Power	Offset energy requirements including for operation, cooling, water treatment and aeration, etc.	Gould and Caplow 2012
	Solar Thermal Heat	Reduces demand on other energy sources to heat greenhouse and building	Goddek et al. 2019
	Geothermal	Coordinated renewable energy source can heat greenhouse and building	Torrellas et al. 2012
	Optimized Light Access	-Roofs facilitate abundant sunlight access, a key resource for effective greenhouse functioning which can be inconsistent and lacking due to shadowing effects in dense urban environs	Ackerman et al. 2013

linkage technologies and synergies like those presented in Table 1. Essentially, system functioning and opportunities to improve efficiency can be assessed as long as one can track, in simple terms: what goes where, in what amount, and how is it changed; and then apply the concept that neither mass or energy are lost or destroyed (though perhaps wasted) within the process. Broad systems integration and efficiency is possible as each open loop is closed or repurposed in a progression toward more sustainable usage of resources and energy in our industrial systems and built environments. Current case studies show that benefits can be realized at different scales. Two possible scenarios are:

- A local micro brewery which could generate competitive advantage related to slow food movement, serving produce and fish they grow on their roof and taking the idea of a culinary garden to a heightened level. One can envision this at a similar scale to BIGH, possible and desirable in a central urban location.

- Large industrial scale integration, where the advantages of a high magnitude of productivity, resource flows, and building capacity would allow for successful commercial operation and profits.

Aquaponics is known to be the most commercially successful and to generate more notable beneficial environmental impacts at industrial scale (Greenfeld et al. 2019). Big breweries can exist in the range of as high as 9 million square feet, creating vast potential for large brewery integrated aquaponic farms as bio-circular buildings that repurpose energy and resource waste into additional production and profit within the same footprint. Often located in peri-urban or rural locations as a result of land availability and prices, industrial buildings can be increasingly synergized with bio-circular processes like aquaponics and power plants that run algae bioreactors to filter exhaust gas to produce biomass, as we design living buildings for a future which integrates and supports sustainable circular economies.

LOOKING FORWARD

Despite increasing commercial and academic interest and expansion in the fields of aquaponics and sustainable BIA independently, the promising potential of BI(Aq), food industry hybrids, and other bio-circular building typologies has not yet been formally assessed and is presently underexplored. BI(Aq) with industrial production processes, like brewing, within the same envelope not only provides programmatic advantages and synergies, but facilitates more sustainable production scenarios that begin to form circular economies. This is due both to the particularly favorable outputs and inputs of the systems, as well as the advantageous nature of industrial buildings with regard to economies of scale. Architects and built environment professionals have a key role in furthering the viability of these potentials, and can be pivotal players in advancing the sustainable impacts and innovative design of these spaces. Future work will consider the possibilities of this means of designing with productive living systems in further technical depth, as well as analyze and document integrative and assessment methods. Utilizing performance and parametric modeling and bringing in expertise, collaboration, and practitioners from biological and engineering fields can form an exciting direction for innovative bio-circular building design. In addition to environmental and economic considerations, there is also more to explore with regards to the human health benefits of biophilic design. The degree to which this also applies to productive living systems will be an interesting and promising interdisciplinary topic of research. Considering urban integration of building-integrated food production is also an important question which design and planning professionals may be particularly well positioned and equipped to address.

Pursuit of impactful circular design, systematic technology review, and development of methodology frameworks to facilitate sound determinations of potential synergies and impacts will be key next steps in holistic research and analysis of BI(Aq). Achieving optimally sustainable food production systems is an increasingly critical interdisciplinary goal which we can help reach by creating cross-sectoral efficiency through innovative design with building-integration of aquaponics and emerging bio-circular production systems.

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