Sourcing Energy from Waste in the Circular City: Integrated Anaerobic Digestion Toward Long-Term Decarbonization of Cities

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Energy use within buildings contributes to nearly a third of carbon emissions in the United States (Zhang et al. 2019, EPA). Meanwhile, between 30-40% of food in the U.S. is wasted and generates carbon emissions equivalent to that of 37 million cars yearly (UN FAO). Long term decarbonization strategies within the built environment can look to alternative energy mechanisms which redirect waste resources as inputs to other systems. Circular City models of sustainability accordingly look for potentials to close loops, turning waste into resources and reducing pollution. These approaches are generating increasing interest and seek to advance a very applied approach to sustainability- one which will integrally require leadership from design fields, local governments, and community leadership to succeed.

Organic material such as food waste contains significant energy which can be processed by the unique metabolisms of microbes into useful gasses and heat. Anaerobic digesters are one such technology which harness microbial capabilities of fermentation to sustainably process resources and harvest energy in a controlled environment from what would otherwise be merely wasted. While anaerobic digesters are often utilized in wastewater treatment and agricultural contexts, they are not yet broadly utilized within cities, even though urban populations and resource consumption continues to rise. We seek here to explore this underutilized potential and ask what it means for buildings, communities, and their designers, who seek to advance increasing sustainability and reduce waste and pollution in the built environment. Case studies and associated carbon footprint impacts will be calculated and analyzed. Finally, opportunities to leverage this long term decarbonization approach will be discussed, and potential environmental impacts to the carbon cycle contemplated in the context of design of current and future sustainable buildings and Circular Cities in an age of increasingly realized anthropogenic climate change.

INTRODUCTION

Anthropogenic climate change is intrinsically tied to cycles of production and consumption, shaping an imperative for long term decarbonization strategies within the built environment to look to alternative energy mechanisms which redirect waste resources as inputs to other systems. The global urban footprint is predicted to triple by 2030 (Seto et al. 2012). Already, as cities consume 60-80% of global natural resources, they create 75% of greenhouse gas emissions and 50% of waste globally (Peter and Swilling 2012). We are in a time where it is crucial for cities to adopt progressively circular systems and economies to diminish global emissions and waste stream magnitudes (Liang and Zhang 2011). Energy use within buildings contributes to nearly a third of carbon emissions in the United States (US EPA). Meanwhile, between 30-40% of food in the U.S. is wasted and generates carbon emissions equivalent to that of 37 million cars yearly (UN FAO). Circular City models of sustainability, as depicted in Figure 1, look for potentials to close loops, turning waste into resources and reducing pollution (Williams 2019). Not limited to urban environments alone in applicability or relevancy, these approaches are generating increasing interest and seek to advance an applied approach to sustainability- one which will integrally require leadership from design fields, local governments, and communities to succeed.

Circular systems are inherent in nature, offering a baseline design framework for ecological equilibrium. Biogeochemical cycles, like the carbon cycle, operate globally and over large time scales. Generally, when organic waste- matter originating from living organisms like plants or animals- decomposes, nutrients and carbon are slowly released and taken up within soils and the atmosphere. However, global industrialization and human interventions in the carbon cycle are tied to the extraction of long buried, carbon rich, organic matter in the form of fossil fuels and the release of CO2 into the atmosphere when these are combusted. Among the many green energy transitions which will be needed in the process of long term decarbonization, the use of anaerobic digestion is one way of more sustainably intervening in the carbon cycle (Figure 2). While anaerobic digesters are often utilized in wastewater treatment and agricultural contexts, both typically located in rural areas, they are not yet broadly utilized within cities, even though urban populations and resource consumption in cities continues to rise (UN 2014).

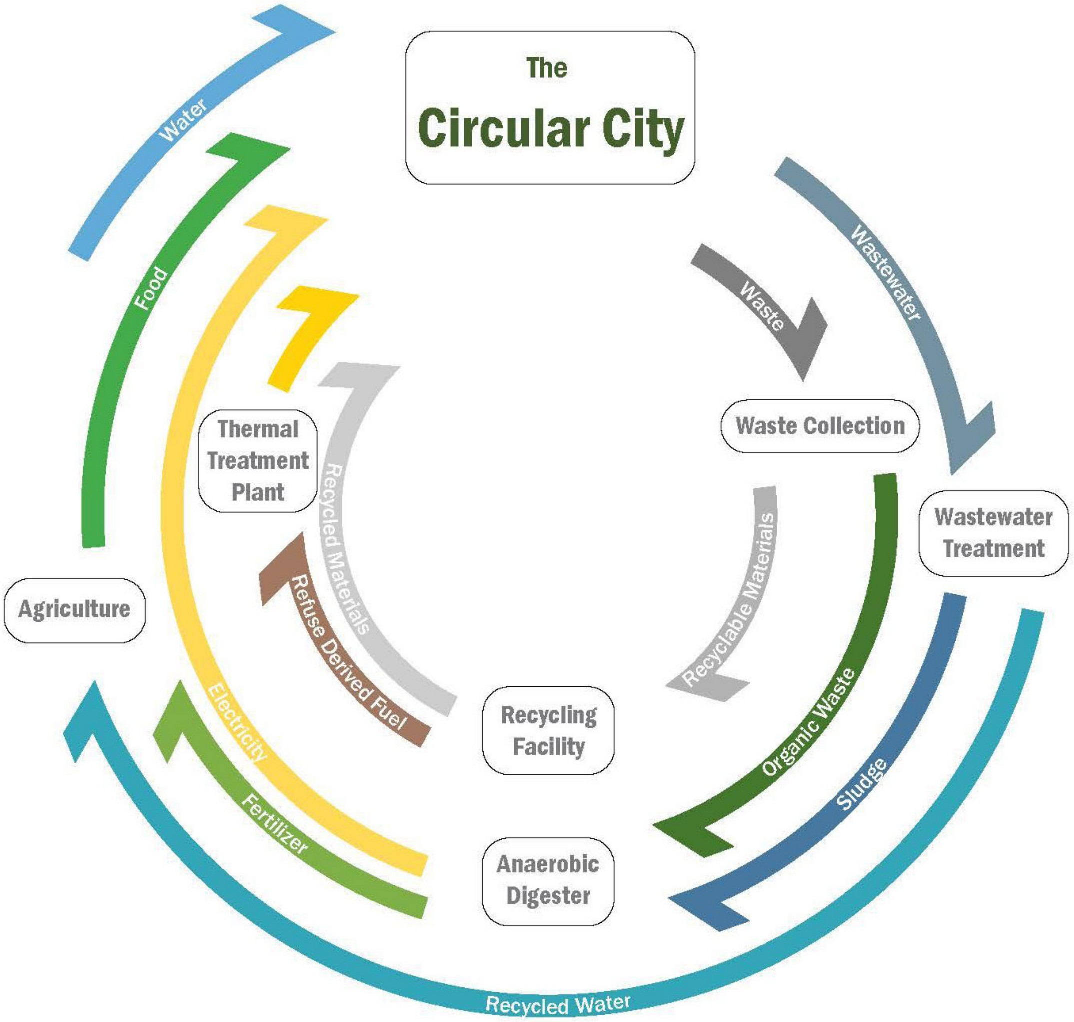


Figure 1: The Circular City Concept, diagram by the authors, inspired by work by the Circular Cities HUB.

In this investigation we seek to explore this underutilized potential and ask what it means for buildings, communities, and their designers, who seek to advance increasing sustainability and reduce waste and pollution in the built environment in an age of increasingly realized anthropogenic climate change. This study will therefore assess approaches to the integration of anaerobic digestion as an alternative energy source taken at building, neighborhood, and city scales through the analysis of case studies, literature, and relevant data.

WHAT IS ANAEROBIC DIGESTION?

Organic material such as food waste contains significant energy which can be processed by the unique metabolisms of microbes into useful gasses and heat (Bautista Angeli et al. 2018). Anaerobic digesters harness microbial capabilities of fermentation to process resources and harvest energy and heat from waste organics in a controlled environment, preventing greenhouse gas emissions of decomposition and recycling nutrients. The process creates nutrient digestate (usable as fertilizer), heat, and biogas, which can be used to generate electricity.

Anaerobic digesters are currently routinely found in rural agriculture and wastewater treatment contexts, but can be integrated into a variety of built contexts and scales, with existing case studies ranging from building to city scale installations. While gaining traction, this potential for a wider variety of implementations, especially in urban contexts, is currently underexplored. Accordingly, in this investigation, a selection of case studies will be reviewed and described, and their scale of carbon impacts compared, to demonstrate the range of design possibilities and decarbonization potential that may exist through the integration of anaerobic digesters in the built environment.

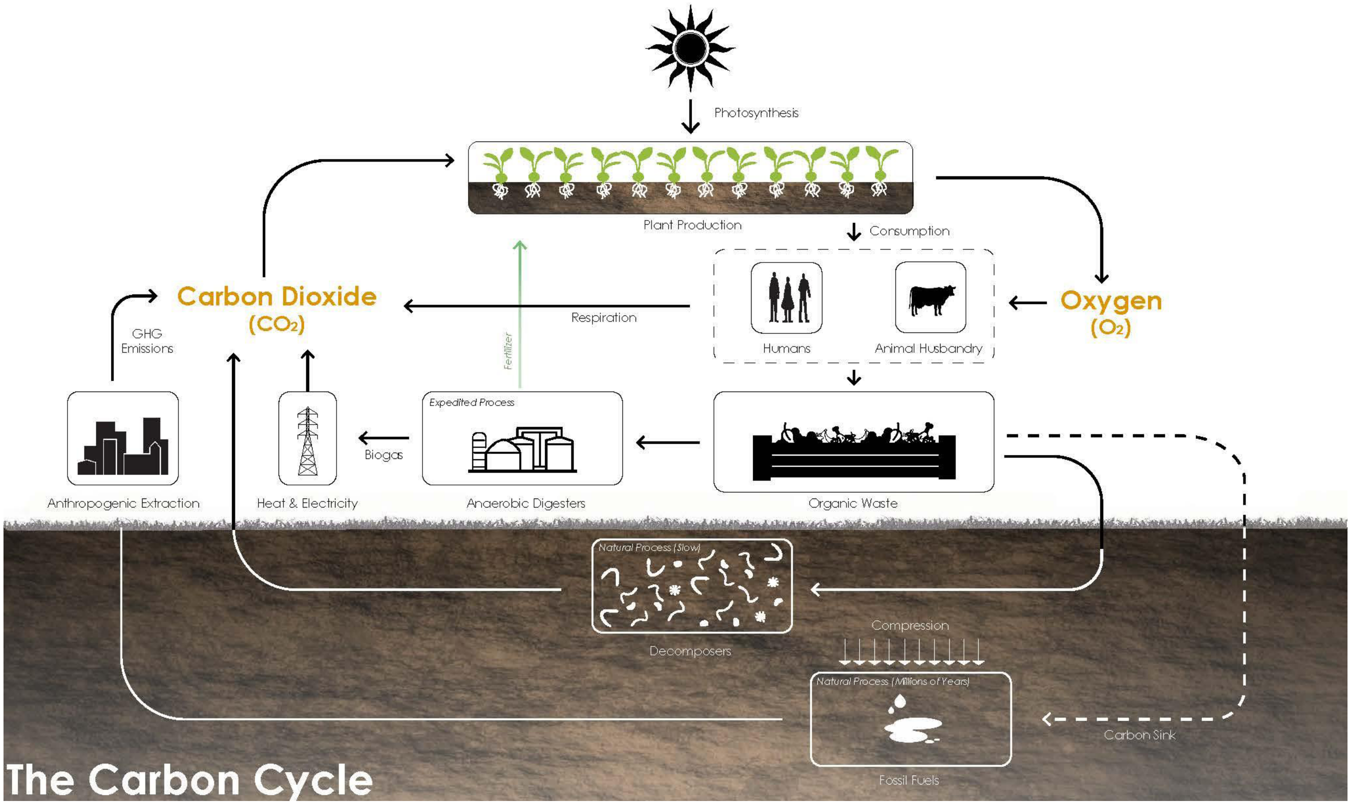


Figure 2: Anaerobic Digestion in the Carbon Cycle, diagram by the authors.

CASE STUDIES

An outstanding example for building integration of anaerobic digestion can be foun.d at The Plant, an “urban food incubator” located in a former meatpacking plant in Chicago. Started by the organization Bubbly Dynamics ten years ago, The Plant aims to facilitate circular economy exchanges largely at a building scale (Chance et al. 2018). The large, historical industrial building houses several food industry operations including a brewery, indoor and outdoor urban farms, a bakery, and a kombucha brewery (Figure 3). In pursuit of increasing resource circularity, The Plant is in the process of starting up an anaerobic digester to provide heat and power to the building while processing organic wastes from the building’s operations and the local food industry (Garcia 2019). Collecting additional organic waste to power the digester allows the scaling of higher resource and energy outputs to support a large, operational, industrial building, and while “waste from the building will be a fraction of the volume of waste processed by the digester... the digester will demonstrate that even food-production businesses, which are typically waste and energy intensive, can operate sustainably by closing waste loops” (The Plant).

While the anaerobic digester being installed at The Plant will require significant organic waste input from the surrounding community in order to sufficiently supply the industrial building, smaller installations exist that can run on less input waste and still provide useful resources for local usage. One such smaller scale example is an anaerobic digester installed at Fremont Brewing in Seattle to turn brewing waste, such as spent hops and grain, into liquid fertilizer used for urban agriculture and gardening and electricity to power cars and bikes. The micro-digester was created by ImpactBioenergy and installed in 2016 (EnergyVision). The system’s cost of $60,000 enables smaller waste generators like Fremont Brewing to create locally usable products at a feasible scale (EnergyVision). The system is off-grid and located in the brewery parking lot where it is housed in a modified shipping container. The biogas it produces provides the heat and energy it needs to operate and excess power is used to supply a generator to charge electric vehicles and bikes (EnergyVision). Brewing waste such as that produced by Fremont Brewery is a good input source for anaerobic digestion, and demonstrates how what is often a waste management issue for brewers can be transformed into the creation of useful byproduct and shape increasingly circular local resource flows. Though brewery organic waste output varies significantly by scale of operation, even small breweries create more organic waste than many comparably sized commercial or residential buildings due to their program. Accordingly, industrial buildings such as breweries can provide a good opportunity for the use of anaerobic digestion due to the higher organic waste they create, and large demand for heat and power they require that might be supplied and offset by the installation of small scale anaerobic digestion.

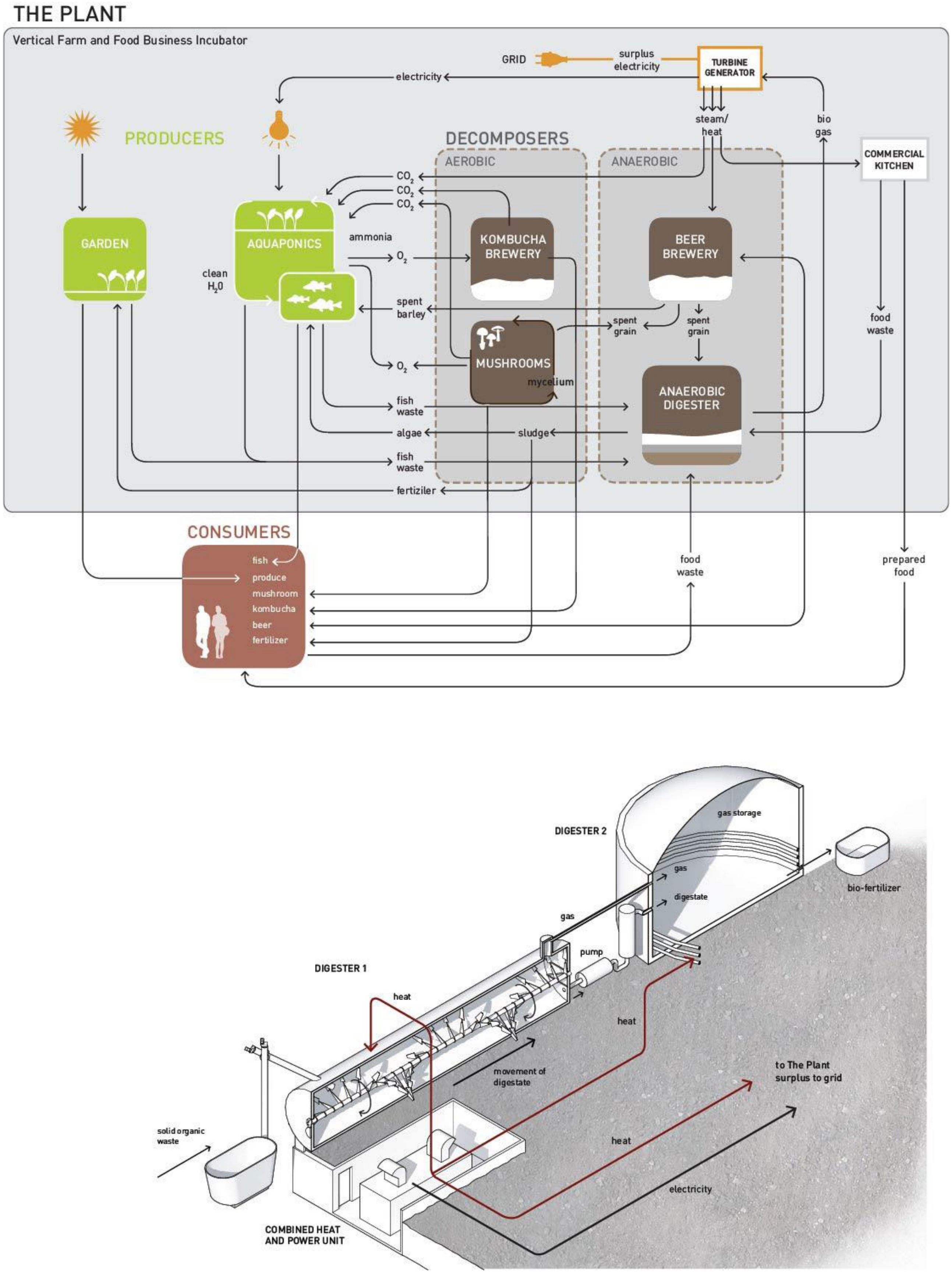


Figure 3: The Plant Chicago Anaerobic Digester and System Integration Diagram, Creating Urban Agricultural Systems (Proksch 2017)

Figure 4: Circular City Comparison, diagrams by the authors.

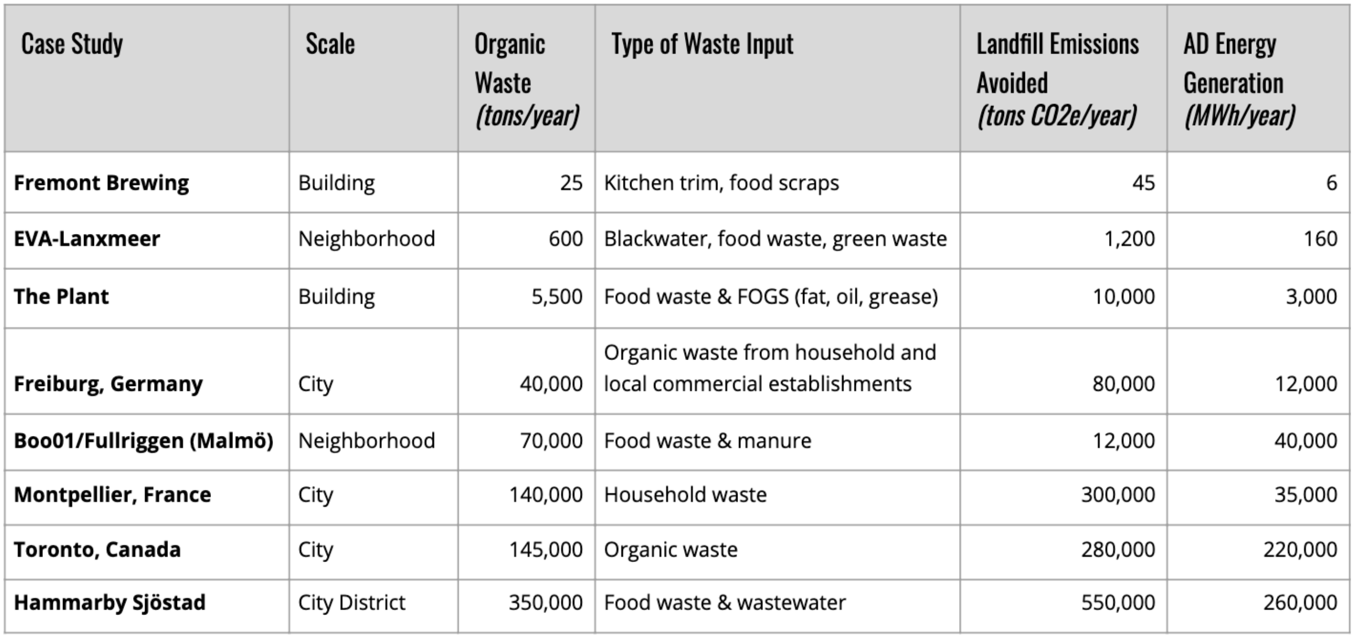
Scaling up from building to neighbourhood or urban district scale can be a good solution to coordinate waste collection and power generation for a larger local region. Several strong examples exist, largely in Europe, and demonstrate the potential for integration of anaerobic digestion as a circular community strategy for decarbonation- and the importance of design in shaping the system integration involved. Hammarby Sjöstad is a sustainable urban district in downtown Stockholm, Sweden, which is a successful example of district scale integration of anaerobic digestion (Bautista Angeli et al. 2018). It is populated by around 25,000 people in about 11,000 residential units. An additional 10,000 people commute into the district for work. The site was a brownfield waterfront zone that started redevelopment in the mid-1990s to bid for the 2004 Olympic Games, but when the city was not selected they decided to make the new district as a model for sustainable urban development (Pandis Iveroth et al. 2013). The city developed "integrated environmental solutions" which have come to be known as the Hammarby model (Bautista Angeli et al. 2018, Fränne 2007). The main source of heating in Hammarby Sjöstad is district heating which is supplied by anaerobic digestion and biofuel. Anaerobic digesters for Hammarby are supplied both by food waste and wastewater treatment, allowing for significant energy production (Figure 4).

A similar example is found in two districts in Malmo, Sweden (Fullrigarren and Boo01) where former ports were transformed into sustainable neighborhoods (Davidsson et al. 2007). While at a smaller scale than the large Hammarby district, both food waste and wastewater are digested to provide heat and power, while the nutrient rich fertilizer created in the process is used to support local agricultural production (Bautista Angeli et al. 2018).

Another neighborhood scale case study of note is located in Culemborg, in the Netherlands. EVA-Lanxmeer is a social-ecological district consisting of 250 mixed housing residences, collective permaculture gardens, business premises, and offices. An anaerobic digestion system was planned but never implemented due to a financial crisis in 2007.

While abandoned, the project remains a model for a Decentralized Sanitation and Reuse (DESAR) concept integrated at the district scale (Bautista Angeli et al. 2018). In addition to sustainable water management, it was designed to contain a small-scale biogas installation for the treatment of blackwater and organic waste to supply a combined heat power (CHP) unit (Bautista Angeli et al. 2018). This anaerobic digestion solution was paired with a closed greenhouse (that can use excess CO2 for plant growth), a Living Machine, and organic food production.

Additional neighborhood and district scale integration of anaerobic digestion has been visioned and planned, but not always implemented. "The 'Zonneterp', a concept originating from Wageningen University in the Netherlands, is a design for a resource independent neighbourhood which would supply its own energy and water. The design includes 100 homes,



Case Study	Scale	Organic Waste *(tons/year)*	Type of Waste Input	Landfill Emissions Avoided *(tons CO2e/year)*	AD Energy Generation *(MWh/year)*
Fremont Brewing	Building	25	Kitchen trim, food scraps	45	6
EVA-Lanxmeer	Neighborhood	600	Blackwater, food waste, green waste	1,200	160
The Plant	Building	5,500	Food waste & FOGS (fat, oil, grease)	10,000	3,000
Freiburg, Germany	City	40,000	Organic waste from household and local commercial establishments	80,000	12,000
Boo01/Fullriggen (Malmö)	Neighborhood	70,000	Food waste & manure	12,000	40,000
Montpellier, France	City	140,000	Household waste	300,000	35,000
Toronto, Canada	City	145,000	Organic waste	280,000	220,000
Hammarby Sjöstad	City District	350,000	Food waste & wastewater	550,000	260,000

Figure 5: Case Study Carbon Impacts Comparison, by the authors.

an energy producing greenhouse, and an anaerobic digester (“Zonneterp”). As a well developed, but hypothetical, example, the community and digester have not been built or fully designed, but speak to the technological potential of anaerobic digestion at community and city district scales.

Scaled up, anaerobic digestion can provide a decarbonizing transition strategy for cities, and shapes an emission reducing waste to energy loop for the Circular City. Integration of anaerobic digestion for urban power production has been implemented in cities including Freiburg, Germany, Montpelier, France, and Toronto, Canada (Bautista Angeli et al. 2018, Gorrie 2015). The City of Toronto, in Ontario, has been expanding their city scale use of anaerobic digestion for waste management and energy generation over the last several years (Toronto Environmental Alliance 2019). While organic waste collection and energy production capacity continues to be scaled up in Toronto, significant energy generation is already being achieved, and the city is progressing toward a goal to have a grid integrated, fully closed loop of waste to energy.

CARBON IMPACT ANALYSIS

Anaerobic digestion helps close the waste to energy loop within the Circular City by moderating human disruption to the carbon cycle. Instead of creating emissions both from landfilled organic waste and fossil fuel combustion, organic waste emissions are avoided while low emissions from anaerobic digestion energy generation are neutral due to the original plant source of the carbon. As a viable strategy within the portfolio of green energy strategies needed for decarbonization of the built environment, it is worthwhile to consider the potential scales of implementation and carbon footprint of anaerobic digester installations. Accordingly, we sought to gauge carbon footprints across the spectrum of case study scales, considering both avoided landfill emissions and anaerobic digester energy generation (Figure 5).

Organic waste input (quantity and type), and energy generated, for each case study was derived from literature documented values for the case studies, and values converted to units of tons/year and MWh/year (Chance et al. 2018, Bautista Angeli et al. 2018, Impact Bioenergy, Gorrie 2015). Avoided landfill emissions (tons CO2e/year) were calculated using literature values for carbon emissions per quantity organic waste by region (Porter and Reay 2016, Hall et al. 2009, Monier et al. 2010).

To contextualize the findings of this assessment, it is notable that eight percent of total global greenhouse gas emissions are created by food waste across the supply chain, comprising 30% of food grown globally (UN FAO). This means that when food waste is compared to the greenhouse gas emissions impacts on global warming of countries around the world, it comes in third after the United States and China (Frischmann, Harvey). Anaerobic digestion to process organic food wastes that are not usable for consumption can help make a dent in this figure. Moreover, there is still a critical need for more clean energy production globally, and in the United States especially, where a transition to a portfolio of green power strategies will make a significant impact. The potential energy outputs of anaerobic digestion can help make a worthwhile contribution. The average annual electricity consumption of residential utility customers in the United States in 2019 was 10,649 kilowatt hours (EIA). This means that an anaerobic digester at the scale of The Plant in Chicago, which is supplied by the building and local community, could provide power to approximately 280 residential utility customers in the United States in a year, while a micro-digester such as at the scale found at Fremont Brewing could supply just over half of the annual energy needed by an average residential utility customer. At larger scales of collection and distribution, such as seen in Toronto and Hammarby Sjöstad, the Circular City can effectively run on a waste to energy cycle and integrate with multiple systems for optimal sustainability.

CONCLUSIONS

Carbon impact analysis of the case studies in this investigation suggests that anaerobic digestion can form a viable integrated strategy which makes use of unused food and organic materials as a means to heat, cool, and power the human landscape from building, to city. Especially with regards to the high carbon footprint of food waste, anaerobic digestion can significantly lower associated carbon emissions while using this waste as a significant resource to help close waste to energy loops within increasingly circular and sustainably designed cities and built environments. As our analysis suggests, there are different ratios of organic matter input to power production depending on system efficiency and type of waste, and in these case studies the scale of installation, inflow, and area supplied power are all unique.

At a building scale, it seems to be more challenging to collect sufficient organic waste for efficient on-site anaerobic digestion, but it can be particularly viable for industrial or agricultural typologies (like brewing or building-integrated aquaponics), and when organic waste input is expanded to collect from local restaurant and other industry wastes. Essentially, when input is scaled up, the heat and electricity produced can supply the building effectively while more sustainably treating the organic waste inflow, which could otherwise cause significant carbon emissions. Potential sources of organic waste span the food supply chain from farms, to stores and restaurants, to individual households. Importantly, addressing hunger by making sure usable food reaches those who need it must be prioritized over slating edible food for energy generation. As food waste is currently generated across the supply chain, solutions, including the approach assessed here of collecting organic material for anaerobic digestion, should reach across this breadth of systems and sources (UN FAO). Likewise, energy and heat supplied by anaerobic digestion can help power electric bikes and cars, buildings, industrial operations, and city grids. The additional output of nutrient digestate can be used as fertilizer for urban and rural agriculture and gardens, and thus support the growth of new consumable produce.

Coordinating organic waste collection and service area can pose a potential logistical challenge at various scales of system integration. At any size of anaerobic digester installation, questions of who will coordinate, who will contribute, who will benefit, and what incentives exist for taking part are vital to successful operation and achieving desired impacts. Policy and design decisions can help further the success of this long term decarbonization strategy, and can start by reimagining how what has previously been viewed as more of a waste management strategy in rural settings can develop into a successful green power generation option for built and urban environments.

The viability of successfully designing and supporting Circular City models of sustainability is intrinsically tied to the sustainable integration of infrastructural systems which can facilitate effective, circular flows of food, water, energy, and materials in the built environment (Jonsson 2000). This investigation suggests that integrating anaerobic digesters in a broader variety of built contexts, especially in cities, can form an effective part of the multifaceted portfolio of green energy transitions that are needed as we seek to build a more sustainable, decarbonized future.

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