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Cornell Campus Metabolism and Circular Economy: Energy, Food Waste, and Construction Materials

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Urban Metabolism (UM) resembles living organisms in a community by consuming necessities and excreting waste. Using a circular economy concept with UM enhances energy and material circulation and closes waste loops. As a campus metabolism case study, this research tracks energy, food waste, and construction materials flows at Cornell University, Ithaca, NY. These sectors are interconnected at the food and energy systems regarding emissions. The study includes environmental and economic evaluations of proposed food waste mitigation and embodied emission estimation of building stocks. The results suggest that transitioning from natural gas to geothermal is a viable renewable option that can increase circularity. Regarding food waste, the proposed digestate composting reduces emissions by 16 to 39 metric tons of CO_2e with a financial gain of 90 to 400 kUS$/y compared to traditional composting practices. Lastly, the comparative assessment of operational emissions from the energy sector and embodied emissions from stored building materials reveals a rising trend in the proportion of embodied emissions contribution, from 53.58 % in 2008 to 73.14 % in 2021. To offset the anticipated release of embodied carbon, Cornell requires strategies to manage construction waste and enhance circularity within this sector. To achieve the decarbonization goal, the campus metabolism study advances the understanding of energy and material flows, emissions, and offsets among the three sectors. This study can unlock sustainability pathways and accelerate Cornell's progress toward carbon neutrality by 2035.

1. Introduction

The increasing consumption of energy and materials is associated with the growing population and their strategies to meet their needs. However, renewable and non-renewable sources of energy and materials cannot keep up with the extraction, manufacturing, consumption, and disposal rate due to current economic practices. Urban Metabolism (UM) conceptualizes the metabolism of living organisms in relation to urban energy and material usage. A population constitutes a community, which leads to activities such as growth, consumption, construction, and waste (Ferrão et al., 2013). Furthermore, humans accumulate materials and energy for future use, following the metabolism concept, which forms a stock and flow (Kissinger et al., 2021). This approach allows for the identification of necessary sources and excretion and improvement opportunities for unnecessary flows related to potential environmental impacts. This study aims to address these impacts and achieve environmental benefits by coupling UM with a Circular Economy (CE) to promote sustainable practices (Ngan et al., 2021). The CE emphasizes optimizing resources extracted, products manufactured, inventory stored, and waste management from an economic perspective (Ngan et al., 2021). Although achieving a full CE where resource extraction is unnecessary is not feasible (Sillanpää et al., 2019), it can lead to sustainable practices by slowing and closing energy and material loops. This study focuses on the energy, food waste, and construction materials of Cornell University in Ithaca, NY, toward achieving campus neutrality goals by 2035. The terms "urban metabolism" and "campus metabolism" are used interchangeably since the campus serves as a living laboratory. The three selected sectors were chosen based on their significant contribution to the environment and the limited research in educational settings. According to the Environmental Protection Agency, electricity generation is the second-largest contributor to Greenhouse Gas (GHG) emissions, especially when the source of energy generation is non-renewable. The major GHG emitters at Cornell University align with the national trend, as the campus's Combined Heat and Power (CHP) plant is fueled by natural gas. Food

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waste is another critical sector with more than 40 percent of the food produced is wasted. Cornell manages food waste by composting with self-generated agricultural waste. Lastly, this study focuses on the construction materials of academic buildings at Cornell since research in this area is often conducted on a city scale (Janjua et al., 2019). For instance, Liu et al. (2022) studied Xiamen, China. This study applies UM to campus contexts and examines the underlying components of the three sectors. By evaluating the energy and material flows, the study identifies system improvements based on technology readiness and the feasibility of economic and environmental benefits. These improvements play a crucial role in generating offsets in total emissions and in achieving Cornell’s neutrality goal. Many universities prioritize improving their GHG emissions in the energy sector through renewable adoptions. However, Cornell University possesses unique characteristics that present opportunities to accelerate circularity within the energy sector. These include the feasibility of geothermal energy and access to a local grid powered by renewable sources. In addition to the energy sector, this paper examines the feasibility of converting food waste to energy, which enhances traditional food waste composting practices. Furthermore, the study estimates the mass of construction materials in Cornell’s academic buildings and approximates the emissions associated with construction waste and embodied materials. This research distinguishes itself from existing campus sustainability studies through three specific research gaps: offsetting embodied construction material emissions with renewable energy and food waste.

2. Method and data

Cornell’s metabolism encompasses multiple components. However, only three sectors are selected to represent the operational activities and structures of the campus. First, an energy sector is necessary to power both academic activities and ensure the well-being of the campus community. Second, food waste is generated from both pre- and post-consumption activities of community members. And the last topic is construction materials, which are used to create physical structures that support academic activities and accommodate the Cornell community. These three sectors have been chosen as representatives due to their integral roles in the functioning of academic activities at Cornell and the availability of quality data pertaining to them. To understand the flow of energy, food waste, and construction materials, Material Flow Analysis (MFA) becomes a valuable tool to identify input, stock, and outflow (Graedel, 2019). Despite controversies that some resources cannot be circulated because of degradation through use, the CE concept mimics the natural circulation process (Cobo et al., 2020). Therefore, this study also performs MFA on the energy sector of Cornell’s main campus, which serves as a living laboratory, to increase circularity and achieve a net-neutral campus goal. The interconnectedness of the three sectors is described in a similar way to the food-water-energy nexus concept (Garcia et al., 2017). For instance, when food waste undergoes composting, it requires water and energy in the treatment process. The generated organic fertilizer by-product can be used as a medium for cultivating new food, thereby illustrating the interconnectedness. Waste-to-energy (WtE) technologies can also convert food waste into an emerging energy source, aligning food waste management with the resource use efficiency of the CE and contributing to the nexus (Al-Ansari et al., 2015). Although the construction and food waste sector may not have a direct correlation, efficient food waste management can offset the operational and embodied emissions associated with buildings (Garcia et al., 2019). Figure 1 shows the three sectors’ connection at the emission and offset levels.

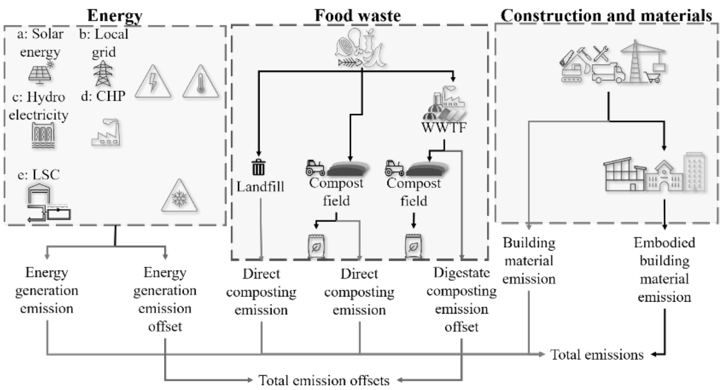

Figure 1: The system boundary illustrates emissions and offsets

The energy sources for campus electricity and heating include solar radiation, hydroelectric power, the local grid (which encompasses sources such as natural gas, hydropower, nuclear, etc.), and natural gas. Additionally, the deep Cayuga Lake possesses a unique geographic characteristic that enables the utilization of the Lake Source

Cooling (LSC) technique to supply chilled water for cooling purposes. This study traces the campus's energy source and consumption patterns from 2016 to 2021 to understand, identify, and plan for improvement. A Sankey diagram is used to illustrate an energy flow analysis, accounting for energy generation and utilization, similar to the MFA. This tool shows the energy composition inflows and outflows for the analysis in section 3.

Since 1997, Cornell has actively composted food waste with a mixture of manure and yard waste (Schwarz et al., 2009). This practice allows the university to divert organic waste from landfills and produce nutrient-rich organic fertilizers for internal use and trade with the local community in Ithaca, NY, promoting a circular economy. However, composting practices are associated with some risks, such as releasing GHGs and odors, despite having well-controlled compost fields (Nordahl et al., 2020). Composting is only one step above the landfill option in the food waste recovery hierarchy. Therefore, this paper proposes digestate composting as an alternative practice and evaluates its environmental and financial impacts. Digestate composting begins with anaerobic digestion (AD), a WtE process, at the Ithaca wastewater treatment facility (IAWWTF). Renewable gas generation from this process moves Cornell up on the EPA's food waste recovery hierarchy (Tian et al., 2020). Solid digestate, a by-product, is composted with agricultural waste to maintain composting traditions and enhance the quality of organic fertilizer production (Song et al., 2021). This approach allows Cornell to exploit the WtE option with energy-offsetting benefits while preserving the self-production of organic fertilizer and its relationship with the local community via organic fertilizer trading (Bora et al., 2020). To compare the performance between traditional food waste and digestate composting, this paper assesses their environmental and financial impacts. The environmental impact assessment utilizes the EPA Waste Reduction Model to estimate GHG emissions and energy savings (Sun et al., 2022). For the financial evaluation, the two options are compared using a linear optimization model subjected to the carbon-to-nitrogen composting ratio and mass balance constraints. The decision variables represent the moisture goal of the digestate suitable for the composting process, establishing a water utilization link in the system (Zhao et al., 2021). The model's objective function minimizes annualized costs of transportation fuel, management, and equipment costs of food and agricultural waste at the IAWWTF and compost field, and the selling price of organic fertilizer. Since composting is an acceptable food waste recovery approach proposed by the EPA, the economic optimization model helps identify potential changes in investments, monetary gains or losses, and whether digestate composting is worth adopting and stepping up the food waste recovery hierarchy.

Construction materials are an intriguing area that has a high impact on the MFA of any community and affects the goal of carbon neutrality. However, only a few researchers have included building materials in their MFA and circularity studies due to the complexity and lifetime of each material type (Janjua et al., 2019). Therefore, this paper proposes an MFA framework to track construction material flows at Cornell. The understanding would allow for better waste management practices and assess future emissions. Note that the intention of this paper is not to suggest or guide future building construction plans. Rather, this study aims to analyze the historical and current utilization of construction materials and evaluate the material flows for future management planning. The quantity of construction materials utilized in academic buildings is determined by calculating the gross construction area and applying the material intensity specific to North American educational buildings. Guven et al. (2022) have classified materials into seven categories. The inflow, stock, and outflows of these construction materials are calculated using equations proposed by Liu et al. (2022). In addition to conducting an MFA, this study estimates the embodied emissions expected to be released during annual building maintenance. The embodied emission coefficients are derived from Hossain et al. (2018) and the Royal Institution of Chartered Surveyors.

3. Results and discussion

The results are presented in three sections: the energy flow analysis, the environmental and economic impacts of direct and digestate food waste composting, and the MFA and embodied emissions of construction materials. The results of the energy flow analysis using a Sankey diagram indicate multiple sources of energy, as shown in Figure 2. The primary energy source for electricity and heat generation on campus is natural gas purchased for the on-site CHP plant. Energy supply also comes from on-campus solar rooftops, grid purchases, and a hydroelectric facility. The metabolism of the energy sector reveals that Cornell primarily relies on non-renewable sources to facilitate campus activities. In addition, the Sankey diagram highlights energy losses associated with natural gas consumption, indicating the presence of infrastructure inefficiencies. Despite renewable projects, emission sinks are not sufficient to offset GHG emissions resulting from natural gas consumption. To achieve circularity by 2035, the university needs rapid actions to reduce natural gas procurement and fully commit to renewable sources. Tian et al. (2022) proposed several mitigation options for transitioning to a renewable energy campus, including the current pursuit of the Cornell University Borehole Observatory (CUBO) project to study Earth Source Heat (ESH) for future heat output. Transitioning from natural gas to geothermal as the primary energy supply would greatly reduce associated GHG emissions and promote circularity within the energy sector.

In addition to the internal efforts and adaptations made by Cornell towards carbon neutrality, the support and commitments from the local government play a crucial role in achieving this goal. The New York Power Authority has committed to supplying 70 % of the grid's energy from renewable sources by 2030 and reaching 100 % by 2040. Therefore, any additional energy requirements from the Ithaca campus are guaranteed to be sourced cleanly by the NYS. The commitments from the university and local government greatly enhance each other, further accelerating the chances of achieving the carbon neutrality goal.

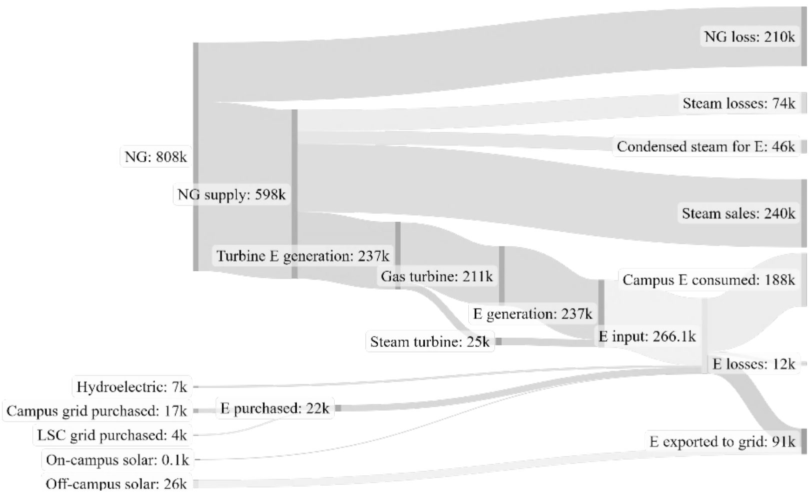

Figure 2: Sankey diagram of energy generation and utilization in 2020. Each flow represents an MWh unit

The economic optimization model reveals that the proposed food waste mitigation has a financial advantage over the current direct composting practice, as illustrated in Figure 3. Both methods include transportation, composting, and management costs. Although digestate composting requires longer transportation time and distance compared to the traditional method, it reduces operational time and energy consumption (Le Pera et al., 2022). The university also receives a tipping fee from the IAWWTF for digestate management. Since the IAWWTF can control the moisture content of the digestate, minimal to no water is needed at the compost field. Additionally, the campus has access to a large volume of digestate to balance carbon-to-nitrogen composting chemistry with agricultural waste and maximize the utilization of the compost field capacity, generating more commercial organic fertilizer. Therefore, in various aspects, digestate composting demonstrates better economic viability compared to direct composting. Note that from 2013 to 2015, both methods generate low economic values due to a significant amount of agricultural waste overwhelming the composting process ratio, resulting in a low output of organic fertilizers and affecting the overall economic composition during those years.

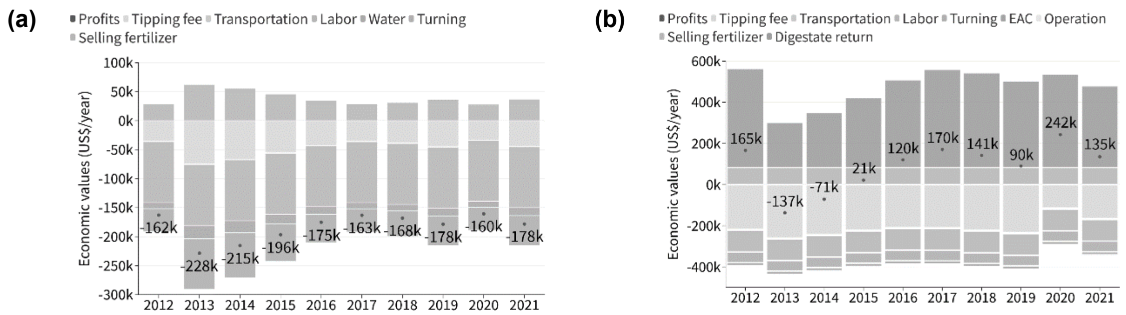

Figure 3: Financial results of the two food waste composting methods are presented in (a) direct composting and (b) digestate composting. The EAC refers to the equivalent annualized cost of a food waste grinder

Several factors contribute to the reduction of GHG emissions in the digestate composting approach. Firstly, the fuel consumption for turning the composting lot is lower due to the shorter composting time, which is a result of increased surface area for reaction. This leads to more efficient composting processes and reduced energy requirements. Additionally, digestate composting benefits from energy offset since the AD of food waste complements biogas for CHP electricity and heat generation at the IAWWTF. The model estimates approximately 135 - 320 MWh of electricity generation per year, highlighting the waste and energy nexus through the waste-to-energy process of digestate composting and providing potential energy offset credits to counterbalance inevitable emissions from other parts of the university (Garcia et al., 2016). Although direct composting is an acceptable food waste management method, the availability of technology at the local AD and the surrounding conditions at Cornell University suggest that digestate composting provides potential attractiveness in both economic and environmental aspects for achieving the carbon neutrality goal.

To estimate stock and flow, construction materials are quantified using a top-down approach. The record of the gross area with material intensities of academic buildings in North America is utilized as a proxy. Inflow includes materials for new construction and maintenance, while outflow represents waste generated during construction and maintenance. The difference between inflow and outflow is considered stocks or the remaining buildings. The construction MFA reveals material intensity consumed and stored, and it can also lead to the estimation of materials' embodied carbon, waiting to be released through waste generation activities. Due to limited studies on construction material emissions, the embodied carbon is estimated per gross area of buildings. When connected with the operational energy usage, the result shows the proportion of total carbon emissions, as illustrated in Figure 4. Although embodied carbon has not been emitted into the environment, an increasing trend in the contribution of embodied carbon has the potential to catch up with operational emissions. Additionally, Cornell's plan to reduce non-renewable energy sources can further accelerate net neutrality in operational energy. Without future planning for construction waste management (Tang et al., 2018), the proportional contribution of embodied carbon from the building materials will soon reach the emission level and overshadow the campus's operational sectors. Thus, construction waste management should be the focus to avoid the emission of embodied carbon, especially when waste from building maintenance activities occurs annually. The university administration may consider collaborating with third-party contractors to ensure circularity in the construction inputs and waste streams or self-circulate used materials, e.g., through reusing and recycling processes.

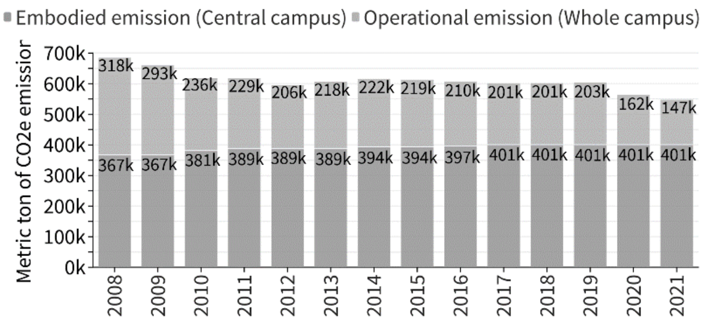

Figure 4: Construction materials embodied emission (bottom) versus campus-wide operational emission contribution (top).

4. Conclusions

This study demonstrated the complexity of achieving a carbon neutrality goal. After analyzing Cornell as a living laboratory in three categories: energy, food waste, and construction materials, information layers were revealed regarding the transition towards a renewable and circular campus. The heavy reliance on natural gas suggested that the university should rapidly transition towards sustainable sources to achieve CE within the sector. The ESH geothermal project and NYS renewable source grids could facilitate this transition. Therefore, carbon offsetting in the energy sector could complement the net neutrality plan through internal changes and support from local legislation. The proposed food waste mitigation method suggested that digestate composting was more favorable from an economic perspective, with a surplus of 90 to 400 kUS$/y, and provided carbon offsets compared to traditional composting practices with 16 to 39 metric tons of CO_2e emission reduction. Lastly, the embodied carbon of stored building materials could not be ignored since the contribution, compared with operational emissions, is expected to grow from 53.58 % to 73.14 % in 2008 and 2021, respectively. Therefore, Cornell needed construction waste management plans to prevent future emissions of embodied carbon and achieve circularity within the sector and the goal of net neutrality of the systems by 2035. Although Cornell was used as a living laboratory, the system framework of this paper could be applied to other institutions for campus metabolism evaluation. In future works, conducting a campus circularity comparison between the current baseline practices and the implementation of renewable efforts would offer a comprehensive assessment of improvement, enabling effective tracking of progress in the future.

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