Resources, Conservation & Recycling 176 (2022) 105939

Contents lists available at ScienceDirect

Resources, Conservation & Recycling

journal homepage: www.elsevier.com/locate/resconrec

Full length article

Synergies of green building retrofit strategies for improving sustainability and resilience via a building-scale food-energy-water nexus

Andrea Valencia [a], Wei Zhang [a], Lixing Gu [b], Ni-Bin Chang [a,*], Martin P. Wanielista [a]

[a] Department of Civil, Environmental and Construction Engineering, University of Central Florida, Orlando, FL, USA
[b] Florida Solar Energy Center, University of Central Florida, Cocoa, FL, USA

ARTICLE INFO

Keywords:
Green building
Food-energy-water nexus
Life cycle assessment
Building resilience
Carbon footprint
Water footprint
Ecological footprint

ABSTRACT

This study examines a green building retrofit plan through a system dynamics model (SDM) creating symbiosis embedded in a building-scale food-energy-water (FEW) nexus. An indicator approach was employed to exploit cross-domain seams via the use of carbon, water, and ecological footprints for sustainability, as well as food security and energy supply reliability ratio for resilience. The SDM was formulated to demonstrate a continuous stormwater treatment outflow model for rooftop farming with stormwater reuse for irrigation, nutrient cycling via the use of green sorption media, and green energy harvesting in support of rooftop farming. We prove that green energy use, stormwater reuse, and rooftop farming can lower carbon, water, and ecological footprints, avoid CO_2 emissions via carbon sequestration in rooftop farming, and improve energy supply reliability and food security. Case 1 (Base Case) includes no retrofit (current condition), Case 2 includes rooftop farming and stormwater reuse, and Case 3 incorporates additional green energy harvesting for sustaining rooftop farming. All three scenarios were assessed using a life cycle assessment (LCA) to generate water and carbon footprints. Case 3 exhibited a 2.24% reduction of total building energy demand from the utility grid due to renewable energy harvesting, while the preservation of nitrogen and phosphorus via the use of green sorption media for crop growth promoted nutrient cycling by maintaining 82% of nitrogen and 42% of phosphorus on site. The ecological footprints for the three case studies were 0.134 ha, 0.542 ha, 6.50 ha, respectively. Case 3 was selected as the best green building retrofit option through a multicriteria decision analysis.

1. Introduction

The coevolution of green building design strategies and urban sustainability solutions has been phenomenal, addressing the impacts of climate change, global economic development, population growth and migration, socio-ecological changes, and rapid urbanization simultaneously. Particularly, advancement toward carbon neutral buildings has increased to address climate change impacts and reduce energy consumption while accommodating energy demand by using low carbon emission sources (Carruthers, 2013). Similarly, carbon negative or climate neutral buildings minimize fossil fuel energy consumption by generating renewable energy; reduction of the carbon footprint of buildings has also been achieved through the use of carbon negative, carbon neutral, and carbon-storing building materials (Pittau et al., 2018). These alternative building materials include bio-based materials like those that are hemp-based (Florentin et al., 2017), straw-based (Carfrae et al., 2011; Pittau et al., 2018), and bamboo-based (Zea Escamilla et al., 2018), all of which are natural renewable resources (Orhon and Altin, 2020). Concrete (Ghouleh et al., 2017; Jami et al., 2016), ferrock (Vijayan et al., 2020), and fly ash (Praneeth et al., 2020) have also been employed for similar purposes. To offset the impacts of global warming and climate change, the Carbon Neutral Design Project was established by the Society of Building Science Educators to provide tools and resources to facilitate zero-energy carbon neutral design (Boake et al., 2008). As part of the initiative from Architecture 2030, the global building energy standard ZERO Code calls for zero-net-carbon buildings through onsite/offsite renewable energy and cost-effective and efficient construction (Architecture 2030, 2020).

However, densely populated urban regions have many existing building infrastructures; therefore, retrofitting buildings is necessary to transition current structures into carbon neutral, carbon negative, or zero carbon buildings. In recent years, sustainable urban systems have

* Correspondent author at: University of Central Florida, Civil and Environmental Engineering Department, 4000 Central, Florida Blvd., Orlando, FL, 32816 United States

E-mail address: nibinchang@gmail.com (N.-B. Chang).

https://doi.org/10.1016/j.resconrec.2021.105939
Received 25 November 2020; Received in revised form 17 May 2021; Accepted 15 September 2021
Available online 29 September 2021

aimed to address fast population growth and curtail carbon emissions via various construction/retrofit initiatives tied to the urban Food-Energy-Water (FEW) nexus, in conjunction with policies and regulations in urban and regional planning (Chang et al., 2020a). Many recent studies have sought to promote sustainability through the implementation of FEW nexus analyses (Ahamed et al., 2019; Hang et al., 2016; Kibler et al., 2018; Newell et al., 2019). Jing et al. (2020) evaluated four building retrofit options for a food-energy-land nexus incorporating rooftop farming and solar energy generation for urban planning decision making. Guan et al. (2020) examined the interactions in a FEW nexus at a metropolitan scale for allocation and management of water resources, and urban FEW nexuses have been increasingly examined (Newell et al., 2019), ranging from case studies and implementations (Ahamed et al., 2019b; Guan et al., 2020; Guta et al., 2017) to various modeling frameworks (Al-Tamimi and Al-Ghamdi, 2019; Bazilian et al., 2011; Hang et al., 2016). For example, an energy-water nexus with a shared microgrid (MG) has been assessed with a focus on renewable energy, since the introduction of an MG improves energy resilience, alleviates water demand, and reduces greenhouse gas (GHG) emissions. This strategy has been simulated and evaluated via its application in a community in Miami, Florida, consisting of a hospital building, a restaurant, a medium office building, and a primary school in the context of a sharing economy (Zhang et al., 2020b).

One current challenge is the development of a unified FEW infrastructure system that integrates different existing and emerging technologies and strategies across the three sectors for urban sustainable development (Chang et al., 2020a). This is also true for a building-scale FEW nexus. For example, most food is transported from remote to peri-urban areas or to cities, resulting in food security issues when natural and man-made hazards occur, such as hurricanes, pandemic, and/or earthquake impacts, which can disrupt the transportation network. Rooftop and garden farming in urban areas, in concert with greenhouse farming in urban and peri-urban areas, could improve the resilience of food supplies, although this would require more local energy and water resources. Renewable energy such as solar, wind, geothermal, low-head hydropower, and wave energy could work synergistically in a small-scale FEW nexus, providing reliable energy for self-sustainment (Chang et al., 2020a, b, c). Stormwater reuse is commonly linked with low impact development-best management practices (LID-BMPs), which include bioswales, stormwater retention basins, stormwater detention ponds, pervious pavement, etc., while LID-BMPs can provide alternative sources of water that are interconnected with, and interrelated to, the food and energy supply chains. Additionally, energy is an important factor, as it is interconnected with and interdependent on the consumption and utilization of the water and food sectors, whether directly or indirectly. However, the symbiosis embedded in FEW nexus solutions showing cross-domain seams with an in-depth indicator approach has not been fully explored at a building scale.

This paper emphasizes a building retrofit plan for the LID-BMP implementation of an FEW nexus analysis at a building scale via an integrative modeling framework to synergize co-benefits across the food, water, and energy sectors via three planning scenarios. Within an integrative modeling framework, a system dynamics model (SDM) was formulated to merge the information flows of the three modeling components: the EnergyPlus (NREL, 2020), the continuous stormwater treatment outflow model (CSTORM) (Hardin et al., 2012), and the best management practices treatment trains (BMPTRAINS). An indicator approach was employed to exploit cross-domain seams via the use of carbon, water, and ecological footprints for sustainability with the aid of a life cycle assessment (LCA), as well as the food security and energy supply reliability ratio within the FEW nexus for resilience. Therefore, the objectives of this study are to: 1) assess building retrofit strategies in a building-scale FEW nexus for rooftop farming using stormwater for irrigation that is simulated to determine the nutrient cycle and energy flow through the integration of three analytical models (CSTORM, BMPTRAIN, and EnergyPlus) in an integrative modeling framework, and 2) quantify the priority of planning scenarios with differing technology implementation options in a building-scale FEW nexus based on a set of sustainability and resilience indicators. Accordingly, the research questions addressed are: 1) How can resilience and sustainability be improved given the transitional implementation of existing and emerging technologies of current building retrofit strategies in an FEW nexus? 2) Can the deployment of a rooftop vegetable garden reduce the annual building energy consumption, contributing to the reduction of carbon emissions and transitioning the current building toward a carbon negative building? And 3) will the integration of renewable energy, urban farming, and LID technologies in a building retrofit plan contribute to an observable reduction in carbon, water, and ecological footprints? We hypothesize that employing renewable energy with LID technologies in support of rooftop farming will promote building resilience and synergize the adjacent communities or buildings, thereby simultaneously improving the environmental sustainability.

2. Methodology

2.1. Case study

The Student Union, located at the University of Central Florida (UCF) campus in Orlando, FL, was selected for demonstration of green building retrofitting for the reduction of carbon, water, and ecological footprints. It is located in the middle of the university campus on sub-basin 4-B, next to two stormwater ponds (wet detention ponds) (4-B1 and 4-B2). This building was constructed in 1996, has an area of 15,027.5 m^2 (161,755 ft^2), and is comprised of retail, event, and student services areas with a daily 15-hour operation, during which the building is expected to have occupants from 9 am to 12 am. A building scale FEW nexus is proposed for the roof, located on the second floor with a total roof area of 306.6 m^2 (3,300 ft^2) (Fig. 1).

2.1.1. Scenario planning

Three building design scenarios, or case studies, were simulated in this study to analyze their impact given the inclusion of food, energy, and water components for green building retrofit (Table 1). Case 1 is the base case, corresponding to the original building design of the Student Union where the original design of the building does not include any of the proposed food, energy, and water components as retrofit strategies. Case 2 introduces rooftop farming (vegetable garden and greenhouse) and stormwater harvesting (wet detention pond/infiltration pond) for irrigation purposes. In Case 2, the roof is divided to allocate 148.6 m^2 (1,600 ft^2) for food production. The rooftop farming system is further subdivided into a 74.5 m^2 (802 ft^2) rooftop vegetable garden for tomatoes with a retention depth of 15 cm (6 inches), and a greenhouse with tomato production spanning 37 m^2 (398 ft^2) and lettuce production over an area of 37 m^2 (398 ft^2). Case 3 builds upon the components implemented in Case 2 with the addition of the deployment of solar PV and VAWT (vertical axis wind turbine) for green energy harvesting. Solar energy harvesting is employed over an area of 153 m^2 (16,470 ft^2), located on the other half of the roof, while 153 m^2 (16,470 ft^2) of the ground area adjacent to the building is proposed for VAWTs. Fig. 2 presents the transition from Case 1 (base) to Case 2 and Case 3 to illustrate the gradual development of the building-scale FEW nexus and its contributions to sustainability and resilience, elucidating the decision making processes regarding sustainability (carbon, water and ecological footprints) and security and resilience (food security, energy supply reliability) in a cyclic decision making process.

2.1.2. Green roof and rooftop farming

In space-limited regions with unoccupied rooftops, roof surface area can be rented or shared for food production, green energy harvesting, and rainwater harvesting (Toboso-Chavero et al., 2019), facilitating the development of an urban FEW system. Given the decrease in potable water sources, stormwater has become a valuable resource. Stormwater

Fig. 1. Student Union rooftop farming with a green energy harvesting (solar PV and wind turbine system) and stormwater reuse plan.

Table 1
Description of Planning Scenarios (Case Studies).

FEW Implementation	Food	Energy	Water	Sustainability Assessment	Resilience Assessment
Case 1	*No rooftop farming*	*No green energy harvesting*	*No stormwater harvesting*	• Carbon footprint • Water footprint • Ecological Footprint	• Food resilience • Energy supply resilience
Case 2	*Rooftop farming:* 1.Vegetable garden (74.5 m^2) 2. Greenhouse (74 m^2)	*No green energy harvesting*	*Stormwater harvesting:* 1.Wet detention pond 2.Cistern storage	• Carbon footprint • Water footprint • Ecological Footprint	• Food resilience • Energy supply resilience
Case 3	*Rooftop farming* (vegetable garden and greenhouse)	*Green energy harvesting:* 1. Solar PV (153 m^2) 2.VAWT (153 m^2)	*Stormwater harvesting:* 1.Wet detention pond 2.Cistern storage	• Carbon footprint • Water footprint • Ecological Footprint	• Food resilience • Energy supply resilience

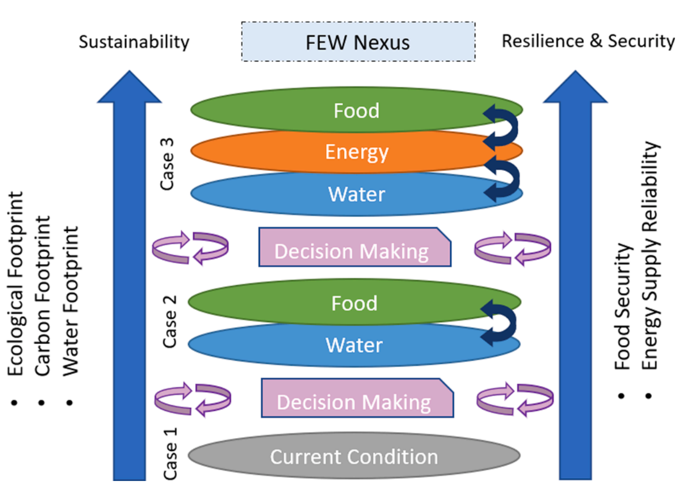


Fig. 2. Schematic flow of transition of FEW nexus implementations in case studies (scenario setting).

harvesting encompasses the collection of runoff (e.g., overland flow) produced from rainfall events via vegetated systems, including bio-retention and swales, and drainage systems such as pipe/channel networks (Mitchell et al., 2007).

However, urban runoff contributes significantly to heavy metals (Cu, Pb, Ni and Zn) (Ermolin et al., 2018), suspended solids, and nutrient (nitrogen and phosphorus) pollution (Grogan and Mallin, 2021), and its impact is augmented by urbanization. The implementation of LIDs such as infiltration trenches, vegetated buffers, green roof, and tree box filters located in strategic areas can attenuate pollution and provide infiltration, retention, and detention in stormwater runoff to decrease stress on paved urban regions. In urban water management, stormwater harvesting reduces the quantity of stormwater runoff, thus reducing pollution of the environment (Zhang et al., 2020a). LID can reduce the exploitation of surface and groundwater sources for non-potable water consumption, including irrigation, which is necessary given the demand for potable water is anticipated to increase by 62% between 1995 and 2025 (Rosegrant et al., 2020).

Apart from being an integral part of an LID, green roofs have also been explored for reducing energy (Sailor, 2008), carbon emissions (Baleta et al., 2019), and heat island effect in urban areas, and are thus an option for sustainable building retrofit (Santamouris, 2014). There are two kinds of green roof, intensive and extensive, which differ in the thickness of the soil layer; the intensive type has a thicker layer of 30 cm or greater (Rasul and Arutla, 2019).

Sonne (2006) investigated the effects of green roofs on energy consumption and performance by looking at different studies conducted on green roofs; one study considered the Student Union, located at the main campus of UCF (Hardin, 2006). The 148.6 m^2 (1600 ft^2) green roof consisted of 0.61 m (2 ft) vegetation and 10–15 cm (4 in to 6 in) of plant media. The two types of growing media utilized in the green roof were green sorption media, consisting of expanded clay, and recycled tire-crumb, the characteristics of which allowed for the treatment of stormwater for quality control. For example, the first media contained 60% expanded clay, 15% perlite, 15% peat moss, and 10% vermiculite. The second media, referred to as Bold & Gold®, consisted of 40% tire crumb, 20% expanded clay, 15% perlite, 15% peat moss, and 10% vermiculite (Hardin, 2006). Additionally, a green roof model for energy simulation was created by Sailor (2008) to determine the energy savings from EnergyPlus (i.e., this model was validated with UCF green roof monitoring data). A green roof energy balance was conducted to compare the building's energy consumption according to varying plant coverage by applying a green roof model with EnergyPlus (Yaghoobian and Srebric, 2015). The study determined a positive correlation between increased plant coverage and reduction in surface temperature, attributed to the decreased absorption of solar radiation.

2.2. *Integrative modeling framework for a building-scale few nexus*

2.2.1. *Green building retrofit strategies*

The integration of various modeling approaches to formulate an SDM enables the construction of an integrative building-scale FEW modeling framework for promoting green building design or retrofit via technology integration. Rooftop farming with stormwater reuse for irrigation can be managed by building an energy balance simulation that incorporates several functional modules to reflect the energy savings created through the presence of green wall and green roof. The CSTORM

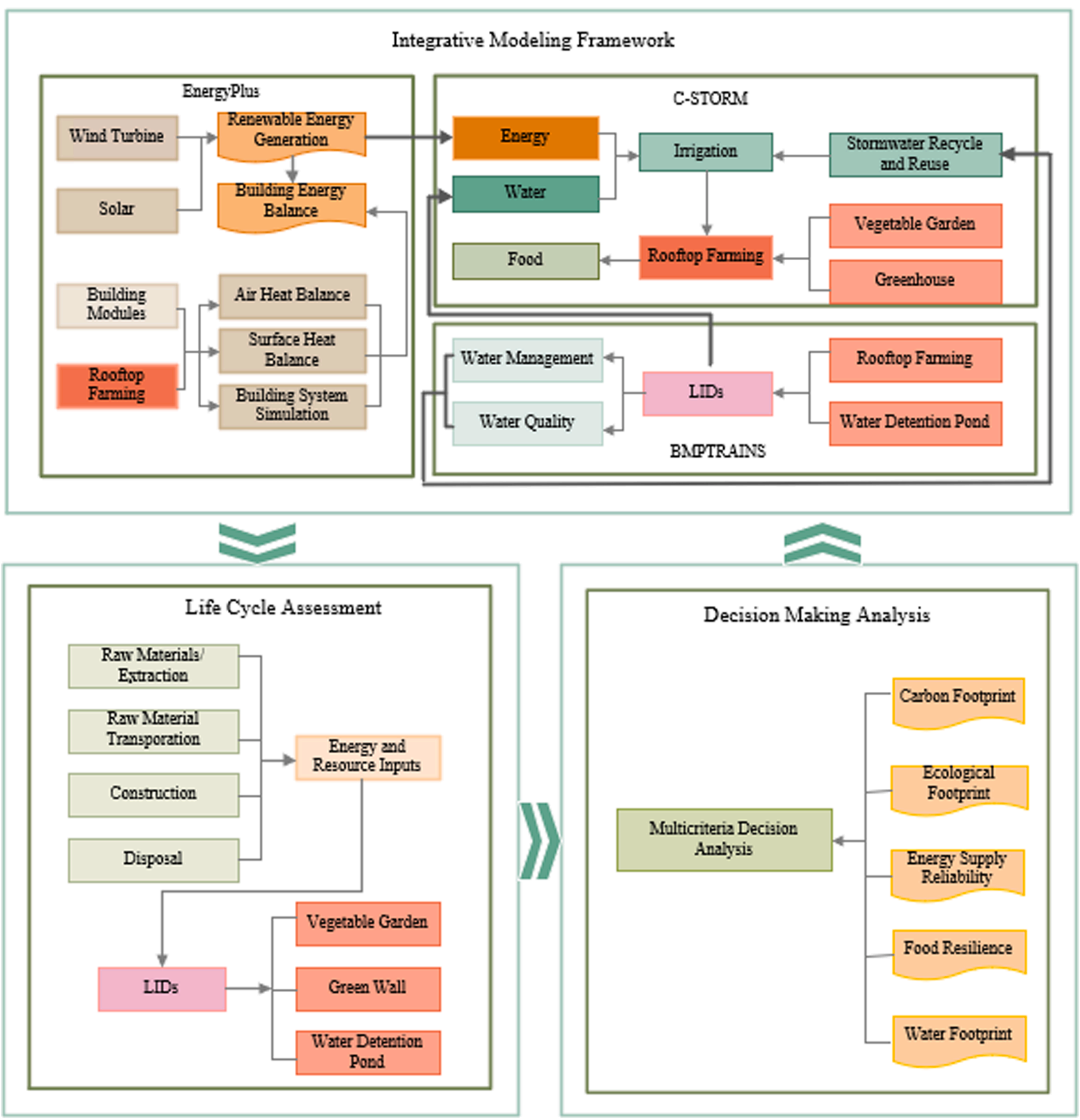


Fig. 3. Data Modeling Framework and Assessment Strategy (including green arrow from decision making using CSTORM).

was developed by Hardin et al. (2012) as a mass balance approach to designing a green roof for stormwater management to reduce stormwater runoff volume and improve its quality. The model encompasses the design of a green roof system in the Student Union that collects and reuses stormwater runoff in a cistern for irrigation. In this context, an expanded SDM, originating from CSTORM (Hardin, 2006; Hardin et al., 2012), which integrates stormwater reuse and recycling, crop production, and nutrient cycling, can be developed in connection with EnergyPlus to build an energy balance analysis, green energy harvesting, and BMPTRAINS (Wanielista and Eaglin, 2020) for LIDs implementation (Fig. 3). The efficiency of LIDs can be evaluated using the BMPTRAINS 2020 program, which was developed to evaluate the effectiveness of stormwater BMPs application in Florida. However, the utilization of BMPTRAINS can be generalized to other regions of interest. Refer to Supplementary Information S1.1. for more information on the employment of BMPTRAINS and LIDs in this study. Coupling common LID technologies is advantageous for supporting the building sector in terms of both resilience and sustainability. For example, two types of LIDs, green roof and wet detention pond, were implemented in the current study to facilitate the FEW nexus at the building scale in a circular economy. Whereas the EnergyPlus, developed by the Department of Energy, enables the investigation of the building energy balance, CSTORM and BMPTRAINS, developed by UCF, empower the large-scale application of LID, mimicking natural hydrological processes toward stormwater reuse and water quality management. In this SDM, CSTORM was formulated by linking stormwater reuse, LID, and roof top farming to bridge EnergyPlus and BMPTRAINS.

The EnergyPlus simulation in this study consists of two components: 1) building energy balance, and 2) green roof effect on energy reduction. The details pertaining to the building energy balance and the effect of green roof on energy reduction are described in the Supplementary Information, along with the EnergyPlus simulation settings used in this study (S 1.2). The building's renewable energy generation was simulated with EnergyPlus for solar PV and VAWT. The VAWT is the most commonly utilized wind energy technology in urban regions due to its suitability for implementation in roof areas or as a stand-alone system (Rezaeiha et al., 2020). The integration of wind energy technologies in an urban FEW nexus has previously been discussed with regard to energy security and avoidance of resource depletion (Chang et al., 2020b, c). The method for calculating the solar PV energy generation according to the PVWatts calculator (NREAL, 2020) is described in the Supplementary Information File (S 1.4), and the power generation of VAWT in a quasi-steady state can be modeled as per the Supplementary Information (S 1.5). Thus, the information retrieved from the aforementioned modeling can be applied to aid in LCA and multicriteria decision-making. The decision-making can promote a cyclic process between the integrative modeling framework and the life cycle assessment, according to the goals of the decision making. This integrative modeling framework synergizes and unifies all the relevant components for green building design or retrofit.

2.2.2. System dynamics modeling

The expansion of the continuous stormwater treatment outflow model (CSTORM) for the green roof stormwater treatment system for green energy harvesting can be included to formalize an FEW nexus. Interchanging the intended stormwater reuse from plant irrigation to vegetable irrigation, the green roof can be converted to facilitate urban agriculture crop production employing green sorption media as a soil substitute. Additionally, the implementation of renewable energy technologies completes the FEW system by supporting the energy demand for irrigation and crop production, as well as the energy demand of the building.

The software STELLA for system dynamics modeling was integrated with the CSTORM to simulate and model the food production, energy consumption, water consumption, and nutrient cycling of the rooftop-farming system with solar PV and VAWT (Fig. 4). The water balance, encompassing the green roof, cistern storage, and wet detention pond, is described in Supplementary Information Eq. S18 (S 2.1). Further, the water and energy consumption demands associated with each crop type, as well as production values related to tomato and lettuce cultivation, are described in Table 2. The harvesting period and harvest rate is included for lettuce and tomato to demonstrate the frequency of

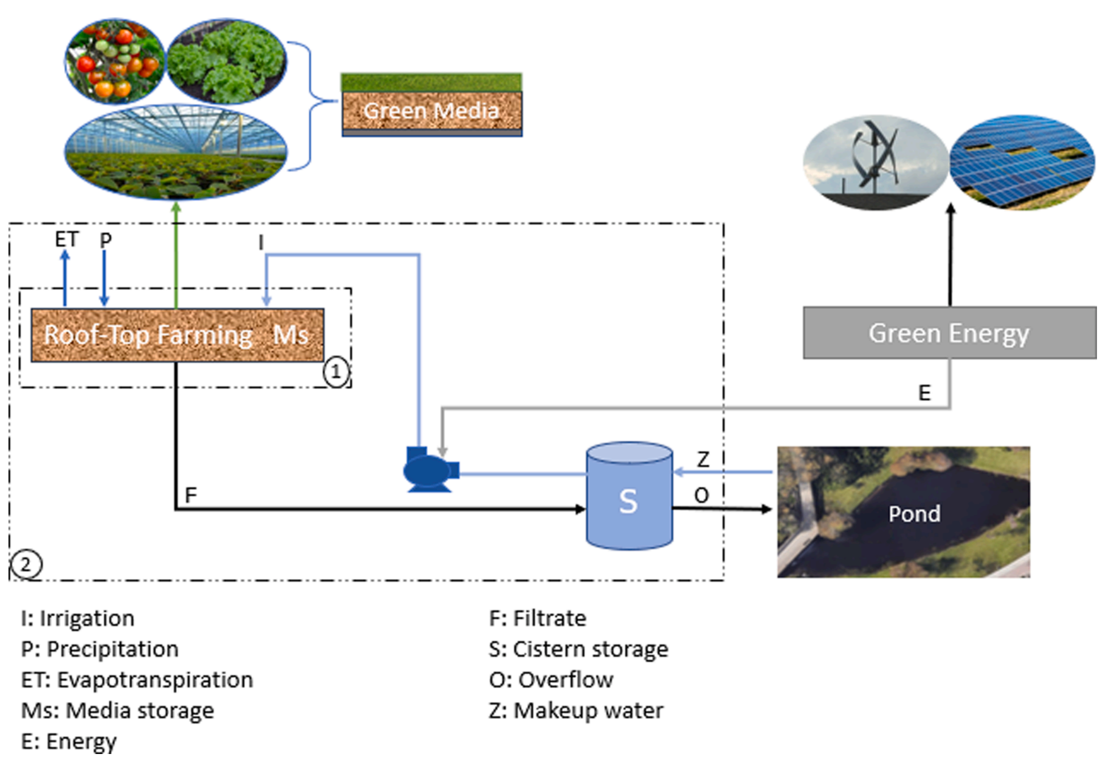


Fig. 4. Expanded CSTORM SDM for green building design. Dash boxes represent mass balance boundaries.

Table 2
Parameter Values of Rooftop Farming in an SDM.

Crop	Water Consumption	Energy Consumption	Production	References
Tomato 1 (Green roof garden)	68.10 L/kg[a]	0.92 kWh/kg[a]	16.3 kg/m^2-yr[a]	[a] Goldstein et al. (2016)
Tomato 2 (greenhouse)	5.95 L/kg[b]	9.18 kWh/kg[a]	9.8 kg/m^2-yr[a]	[a]Goldstein et al. (2016) [b]Ntinas et al. (2017)
Lettuce (greenhouse)	20 L/kg[c]	148.57 kWh/kg[a]	0.7 kg/m^2-yr[a]	[a]Goldstein et al. (2016) [c]Barbosa et al. (2015)

harvesting and the number of crops harvested annually.

To address stormwater water quality and the effect of nutrient cycling, nutrient retention in the green sorption media was considered in the CSTORM design. With the application of green sorption media such as BAM and IFGEM (Chang et al., 2018, 2019) as the vegetable garden soil mix, nitrogen and phosphorus nutrient cycling could be addressed. The TN and TP remaining in the media mixture are expressed in Eq. S19, and pertinent nutrient cycling parameters are found in Supplementary Information S2.1.

Defining the appropriate input data for simulation is essential for obtaining adequate simulation results. The data provided to the SDM pertaining to the monthly precipitation, evapotranspiration, filtration, and solar electricity generation are defined in Table 3. Additionally, the solar and wind electricity generation obtained from the PV and VAWT systems was input for modeling. The SDM formulated through the component-based graphic user interface in Fig. 5 exhibits the integrative modeling framework.

2.3. LCA for a building-scale food-energy-water nexus

An LCA study can aid in the evaluation of the impacts and benefits of infrastructure for decision-making, especially when there is insufficient LCA data available with respect to the water footprints of agriculture technologies like green roof and greenhouse. In general, green roof and greenhouse LCA analysis has focused primarily on GHG emissions and carbon footprint (Bhatt et al., 2019; Chen et al., 2018; Langston, 2015; Pirouz et al., 2020), with some studies examining the water footprint reduction (Pirouz et al., 2020) and water quality and energy consumption from green roof (Hashemi et al., 2015). Therefore, our LCA analysis focused on the evaluation of green roof, greenhouse, and wet detention pond for water and carbon footprints associated with the building-scale FEW nexus. The LCA was formulated with respect to sustainable expansion with the functional unit being one green building with the 100-year life span of a green roof, greenhouse, and wet detention pond with treatment areas of 74.5 m^2, 37 m^2, and 8652 m^2 for green roof (vegetable rooftop), greenhouse, and wet detention pond (stormwater pond), respectively. SimaPro® software was used to address the sustainability impact of these green building components with regards to carbon emission and water footprint. Assessment was performed using the IPCC 2013 WPC 100a method, and the available water remaining code (abbreviated as AWARE), according to the ISO 14046 methodology, to quantify the carbon and water footprints, respectively. Therefore, the "cradle-to-grave" LCA for the LIDs, green roof and greenhouse was considered for this assessment, encompassing the manufacturing, construction, transportation, and decommissioning of the infrastructure, as depicted in Fig. 6.

Further description of the LCA methodology, the summary of the life cycle inventory (LCI) and the components of each technology analyzed for LCA, are described in Supplementary Information S2.2. The components of an extensive green roof include structural support, decking, insulation, underlayment, water proofing membrane, drainage layer, filter fabric, soil medium, and membrane protection (Table S4) (Kosareo and Ries, 2007). The components of the wet detention pond include a liner, drainage layer, and soil media (Table S5). Further, the components of the greenhouse include structural support, cover, and flooring (Table S6).

2.4. Building sustainability assessment

Building sustainability was evaluated with respect to the carbon, water, and ecological footprints utilizing existing LCA results from published literature and this study collectively. The carbon footprint assessment in this study corresponded to the contribution of carbon emissions (kg $CO_{2\text{-eq}}/m^2$) in GHG for energy generation (e.g. utility and renewable energy), crop production, and retrofit technologies (LIDs and greenhouse) (Eq. (1)). The GHG emissions pertaining to renewable energy technologies and crop production including transportation were obtained from literature, as referenced in Supplementary Information S 2.3

$$CO_{2footprint} = CO_{2utility} + CO_{2crop,local} + CO_{2Ren.\ energy} + CO_{2technologies} \quad (1)$$

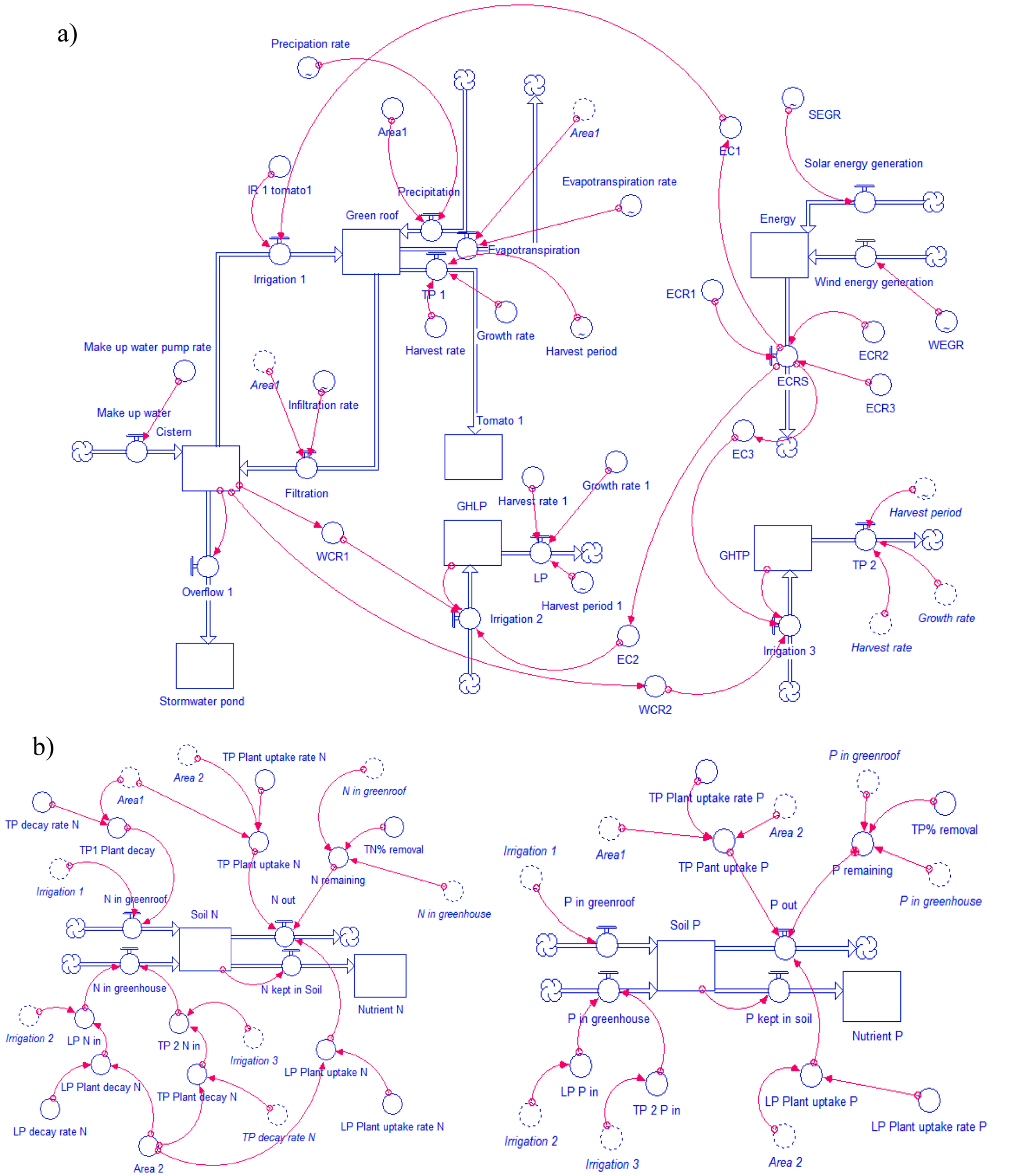
Here $CO_{2_{footprint}}$ = carbon footprint in kg $CO_{2\text{-eq}}$, $CO_{2utility}$= $CO_{2\text{-eq}}$ emission for the utility grid for energy generation (e.g. carbon and natural gas), $CO_{2Ren.\ energy} = CO_{2-eq}$ emission from renewable energy (PV and VAWT), $CO_{2technologies} = CO_{2-eq}$ emission for green building retrofit technologies (e.g. LIDs and greenhouse), and $CO_{2crop,local} = CO_{2-eq}$ emission for local crop production. Here, carbon sequestration from crops is assumed to be negligible.

Likewise, the water footprint assessment quantifies water utilization (m^3) for energy generation and crop production and incorporates the reduction of freshwater utilization via its replacement with stormwater in crop cultivation, and water use reduction from renewable energy

Table 3
Data of the Student Union for SDM.

Month	Precipitation rate mm or (inch)	Evapotranspiration rate mm or (inch)	Filtration rate mm or (inch)	Solar electricity generation (kWh)*	Wind electricity generation (kWh)*
January	87.12 (3.43)	62.23 (2.45)	5.08 (0.20)	2649	2721
February	35.56 (1.40)	47.24 (1.86)	7.62 (0.30)	2464	2528
March	45.72 (1.80)	43.75 (2.51)	8.89 (0.35)	3239	3366
April	48.01 (1.89)	77.72 (3.06)	6.10 (0.24)	3378	3251
May	113.79 (4.48)	90.42 (3.56)	8.38 (0.33)	3390	2366
June	311.40 (12.26)	87.88 (3.46)	11.43 (0.45)	2952	1804
July	159.26 (6.27)	102.85 (4.05)	11.68 (0.46)	3006	1909
August	330.96 (13.03)	105.66 (4.16)	10.92 (0.43)	2975	1301
September	75.69 (2.98)	87.88 (3.46)	10.16 (0.40)	2753	2576
October	144.27 (5.68)	80.26 (3.16)	7.12 (0.28)	2920	2351
November	33.78 (1.33)	53.09 (2.09)	3.56 (0.14)	2558	1618
December	81.79 (3.22)	45.47 (1.79)	4.83 (0.19)	2370	2548

*EnergyPlus PV generation results.



IR: Irrigation rate; TP 1: Tomato Production green roof system; GHLP: Greenhouse system lettuce production; LP: Lettuce production; GHTP: Greenhouse system tomato production; TP 2: Tomato Production greenhouese system; WCR 1: Water consumption rate LP; WCR 2: Water consumption rate TP 2; EC 1: Energy consumption TP 1; EC 2: Energy consumption LP; EC 3: Energy consumption TP 2; ECRS: Energy consumption rate sum; ECR 1: Energy consumption rate TP 1; ECR 2: Energy consumption rate LP; ECR 3: Energy consumption rate TP 2; SEGR: Solar energy generation rate; WEGR: Wind energy generation rate; LP N in: Nitrogen introduced from lettuce production; LP P in: Phosphorus introduced from lettuce

Fig. 5. (a) Expanded CSTORM SDM for Green Building Design with Green Roof, Solar PV, and VAWT System; (b) Nitrogen and Phosphorus cycling in the rooftop soil.

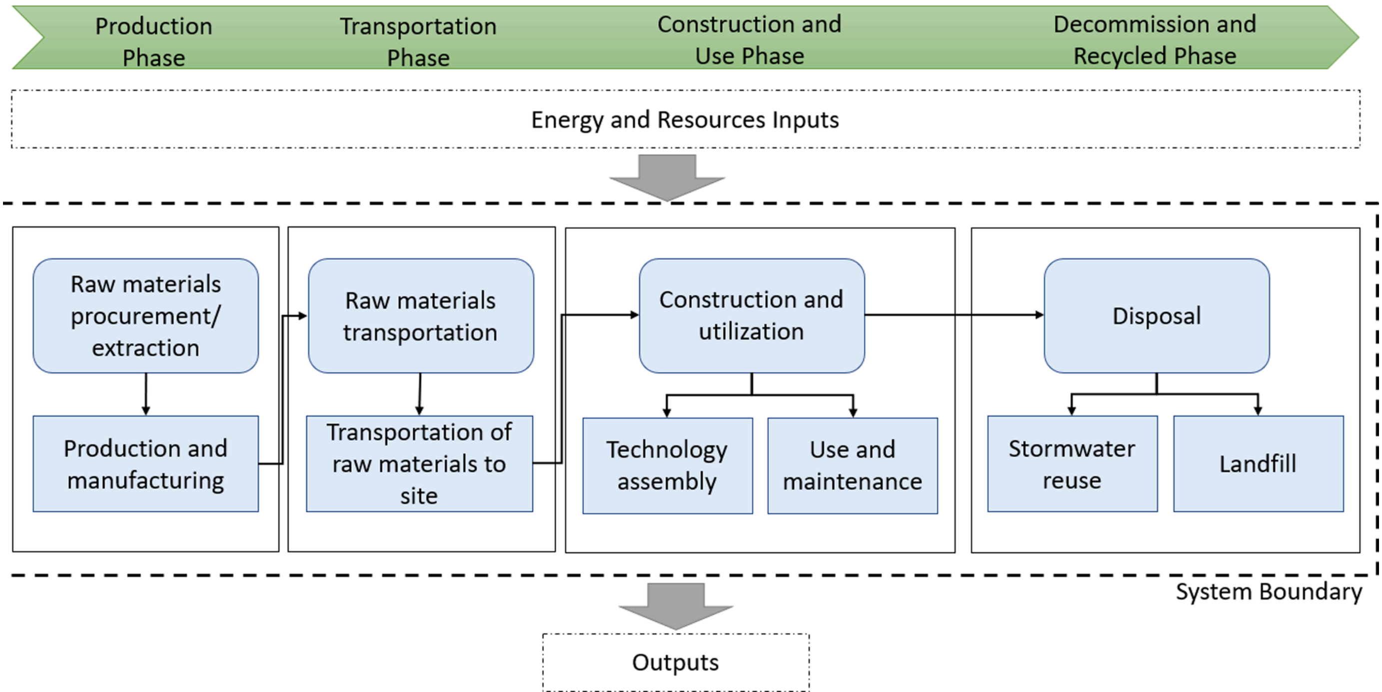


Fig. 6. LCA analysis for LID (green roof and wet detention pond) and greenhouse process schematic.

generation (Eq. 5). The water consumption values utilized in the analysis that are extracted from literature are described in S 2.3.

$$W_{footprint} = W_{utility} + W_{crop} + W_{Ren.\ energy} + W_{technologies} \tag{2}$$

where $W_{utility}$ = water consumption for the utility grid for energy generation, W_{crop} = water consumption associated with crop production, $W_{Ren.\ energy}$ = water consumption from renewable energy technologies (PV and VAWT), and $W_{technologies}$ = water consumption from retrofit technologies (e.g. LIDs and greenhouse).

Furthermore, the ecological footprint of land use can be determined from the consumption, production, imports, and exports of products or waste, including the carbon, cropland, fish grounds, forest, and built-up land footprints (Eq. (3)) (Lin et al., 2018).

$$E_{footprint} = E_{carbon} + E_{cropland} + E_{fish\ ground} + E_{forest} + E_{built-up\ land} \tag{3}$$

where E_{carbon} = carbon footprint, $E_{cropland}$ = cropland footprint associated with land utilization for agricultural production, $E_{grazing\ land}$ = land use required to feed livestock, $E_{fish\ ground}$ = land utilization for fisheries on aquatic ecosystems, E_{forest} = land utilization for wood supply, and $E_{built-up\ land}$ = land use of infrastructure. Here cropland and grazing land footprints are interconnected. For simplicity, and given the site description, the $E_{fish\ ground}$ and $E_{grazing\ land}$ will not be addressed in the ecological footprint calculation. Each footprint i can be calculated as follows (Eq. (4)) (Borucke et al., 2013):

$$E_i = \sum^{\frac{P_i}{Y_N}} * YF_N * EQF_i \tag{4}$$

here P_i = produced or harvested product, Y_N = annual national average production yield, YF_N = specific yield factor based on country, and EQF_i = equivalence factor for land use.

Hence, using Eq. (1) and Eq. (2), the carbon and water footprint sustainable indices were calculated for the three cases by inputting the GHG emissions and water consumption factors from the retrofit strategies described in Table S10 and S11, acquired from literature, and LCA into STELLA SDM, as visualized in Fig. 7.

2.5. *Building-scale few nexus resilience analysis*

Whereas sustainability level can be determined via indicators like carbon, water, and ecological footprints, food security and energy supply reliability ratios can be used for resilience assessment at the building scale. The food security indicator is defined as the self-sustainment ratio, whereas the energy supply reliability ratio is defined as energy supply resilience, to be defined mathematically later. In turn, these indicators help reinforce the applicability of green building design or retrofit by addressing the interactions among the food, energy, and water sectors at the building scale. Additionally, the self-sustainment ratio can be used as an indicator of resilience in the food sector regarding food self-sufficiency (Eq. (8)). Thus, the ability of a population to satisfy food requirements can be quantified with this indicator; a self-sustainment ratio (*SS*) of 1 indicates a balance between food production and consumption. Higher or lower self-sustainment ratios suggest excess food supply or food deficit, respectively. A population of 500 individuals with an average consumption of 4 kg of food per day per person for a proper diet (Organization, 2003) was used for food resilience assessment.

$$SS = \frac{F_{produced}}{F_{consumed.}} \tag{8}$$

where *SS* is self-sustainment ration (used in food resilience assessment), $F_{produced}$ is the total food produced from local crops, and $F_{consumed}$ represents the average food consumption in the community.

To signify the energy supply resilience, the energy supply reliability ratio (r_{es}), is defined as Eq. (9):

$$r_{es} = \frac{EENS}{E_{total}} \tag{9}$$

where *EENS* is expected energy not supplied in a year, and E_{total} is the annual energy consumption of the building. The building loads can secure energy supply from three resources: wind turbine, solar panels, and the utility grid; we can apply the Monte Carlo method to determine the *EENS* in a year (8760 h). To determine *EENS*, we needed to decide on the values of the fault rate and the mean time to repair (MTTR) of these components, which are given in Table S12. MTTR is a basic measure of

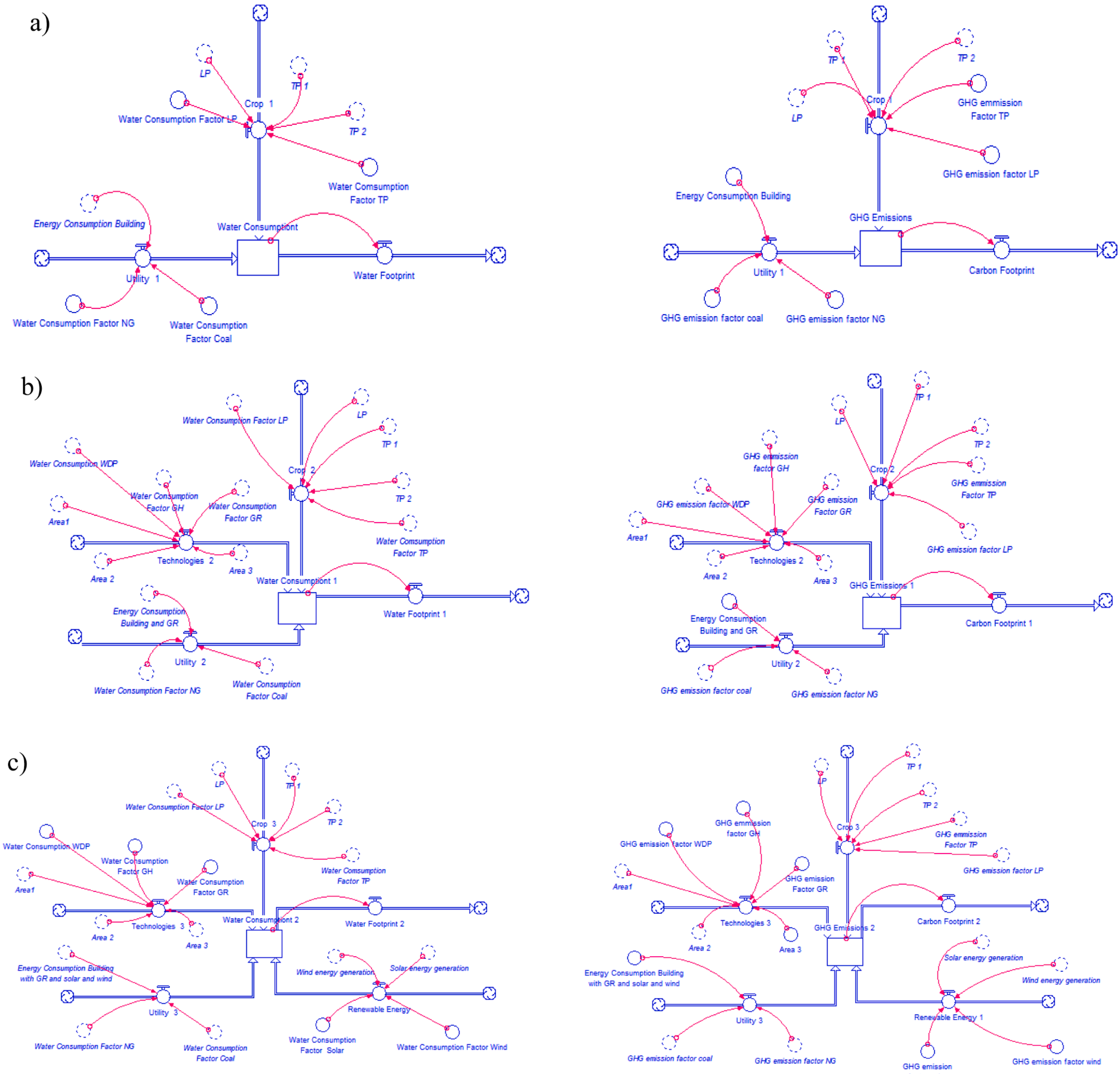


Fig. 7. SDM for water and carbon footprint calculations for a) case 1, b) case 2, and c) case 3.

the maintainability of repairable items (Zhang et al., 2020b).

2.6. Assessment of retrofit strategies

By synthesizing and merging the distinct green building components and environmental impact, a decision-making process for determining the most appropriate planning scenario for green building retrofit can be performed. The water, carbon, and ecological footprints can be utilized collectively to determine which building retrofit alternative is more sustainable in a multicriteria decision making analysis (MCDA). The distinct decision-making alternatives can be assessed on multiple weighted criteria according to technique for order preference based on similarity to the ideal solution (TOPSIS), in which the alternative with the largest performance score is preferred (Wang et al., 2009). The description of TOPSIS methodology is explained in Supplementary Information S 2.5 (Eq. S20–26). For analysis, the weighted criteria included the carbon, water, and ecological footprints, energy supply reliability ratio (r_{es}), and food security (*SS*). Since all the criteria are crucial indicators of sustainability and resilience, all 5 criteria were assigned a weight of 20%.

3. Results and discussion

3.1. Green energy harvesting

The total energy generation from solar PV and wind VAWT was simulated in EnergyPlus for an area of 153 m^2 (1650 ft^2) in Orlando, Florida. The total annual solar PV energy generation was determined as 124.92 GJ (3.47 $(10)^4$ kWh), or a monthly average of 10.4 GJ (2.89 $(10)^3$ kWh). Additionally, the total annual wind energy generation was modeled as 101.9 GJ (2.83 ($10)^4$ kWh), or a monthly average of 8.50 GJ (2.36 $(10)^3$ kWh). Since both renewable energy technologies generate energy, incorporating both solar and wind energy technologies in an urban FEW nexus can enhance community resilience (e.g., reliability of power supply) and environmental sustainability (e.g., less GHG emissions). The renewable energy generation is sufficient for maintaining the annual operation of the rooftop vegetable garden and sustaining 2.24% of the total building energy demand. Further, with the inclusion of the reduction in cooling and heating demand by the rooftop garden, modeled as a green roof and renewable energy, the energy demand is reduced by 2.29%, therefore reducing the demand on the utility grid. If green energy harvesting is increased to sustain the entire building energy demand, any excess energy generated could be stored for future use or directly supplied back into the electricity grid through smart metering, helping transition the Student Union to a carbon negative building by reducing its dependency on the electricity grid. Despite using various assumptions to generate the solar PV and wind energy generation, and estimating the Student Union energy demand, these results are considered reliable representations of the energy demand. The green energy harvested could be either consumed locally via an MG or stored in lithium-based batteries for future use (Zhang et al., 2020b). An MG with energy storage devices could be managed as a community-scale public good in a sharing economy with the addition of more green buildings.

3.2. Building energy consumption

A building energy balance enables understanding and simulating building energy performance and consumption based on stipulated input parameters. The utilization of EnergyPlus provides a forecast of the energy consumption of the Student Union. As a form of validation, the simulated building energy consumption from EnergyPlus can be compared with the recorded Student Union energy consumption, which includes electric, chilled water, and gas. The annual building energy demand of 2.13 $(10)^4$ GJ (5.93 $(10)^6$ kWh) was acquired from the UCF Open Energy Information System for the time period of 01/01/2019–12/31/2019. However, EnergyPlus was utilized to unify the energy consumptions determined for the building, green roof, and renewable energy. Based on EnergyPlus, the total base energy demand of the Student Union without the inclusion of the rooftop farming and green energy harvesting was modeled as 1.013 $(10)^4$ GJ (2.81 $(10)^6$kWh). The electric, gas, and cooling consumptions were simulated as 9.71 $(10)^3$ GJ (2.70 $(10)^6$ kWh), 417.60 GJ (1.16 $(10)^5$ kWh), and 1.45 $(10)^3$ GJ (4.03 $(10)^5$ kWh), respectively. However, a discrepancy was observed when comparing estimates with the annual building energy demand of 2.13 $(10)^4$ GJ (5.93 $(10)^6$ kWh) acquired from the UCF Open Energy Information System. A possible cause for the simulated total energy demand being only half of the energy demand acquired from the Student Union building database may be related to the internal energy gains, which EnergyPlus cannot reflect. In addition, weather data used in simulation may be typical, instead of real weather, thus climate differences may also contribute to energy consumption differences. Further, the aging of appliances may have reduced the building's energy consumption efficiency, and the utilization of the entrance doors can contribute to the escape of airflow, which can increase the energy demand attributed to the maintenance of the building temperature. However, the results from EnergyPlus support the understanding that the implementation of a vegetable garden reduces total energy consumption by obtaining a decrease in total site energy consumption (Table S13). Although the reduction in building energy consumption is minimal, an energy reduction of 0.15% was observed between Case 1 and Case 2 with the integration of a vegetable garden on the Student Union roof. A larger reduction in energy consumption can be expected when increasing the surrounding area of the vegetable garden to mitigate the urban heat island effect.

3.3. Expanded CSTORM SDM

The results from the expanded CSTORM SDM analysis incorporated the tomato and lettuce production occurring after approximately 3 months of seeding to harvesting (growth rate) (Table 4), which corresponds to the appropriate time required for vegetable seeds to germinate , and the number of crops possible per year for each crop type. Furthermore, a higher annual yield in production was achieved for the tomato crop (513.76 kg/yr) cultivated via the green roof in comparison to the greenhouse (153.4 kg/yr). While a total of 691.15 kWh per month or 8.29 $(10)^3$ kWh per year was modeled as the total green roof and greenhouse energy demand, this energy demand is mostly linked to energy consumption related to the pumping of water for irrigation.

Nutrient cycling is crucial for assessing an FEW system due to the importance of the resource depletion of minerals, such as phosphorus employed in fertilizers (Leghari et al., 2016). Modeling the nutrient cycling in this study helps address stormwater water quality management in terms of nitrogen and phosphorus. Based on the range of nutrient removal via IFGEM sorption media, the total nitrogen and total phosphorus removal efficiencies of 80% and 50%, respectively, were applied in the modeling analysis. The results demonstrate the preservation of nitrogen and phosphorus in the green sorption media for nutrient control can promote nutrient cycling by adsorbing around 1175 kg/yr of nitrogen (82%) and 52 kg/yr of phosphorus (42%) for crop growth (Table S14). It was also determined that the contribution of plant uptake to nitrogen and phosphorus was minimal in comparison to the nutrients carried over from the irrigation water and removed from the green sorption media. Further, the utilization of BMPTRAINS for a supplementary simulation enabled the determination of the appropriate LID technology assessment for stormwater reuse, which can be applied for rooftop farming and landscape architecture design around the building retrofit. The examination of a wet detention pond LID is discussed in Supplementary Information (S3.3). Results suggested the inclusion of the green roof provides 90% nitrogen and phosphorus treatment given nitrogen and phosphorus loads of 0.46 kg/yr and 0.08 kg/yr, respectively. This indicates that the utilization of green roof and rooftop farming can help manage nutrient recycling and possibly recover some nutrients, supporting nutrient cycling in the expanded CSTORM SDM analysis. Based on these results, if green sorption media such as BAM or IFGEM (Chang et al., 2018, 2019) were implemented as the media mix instead of traditional growth soil, the spent media mix could be replaced and used as a soil amendment, hence improving the environmental sustainability of the FEW nexus.

3.4. LCA for green building

A "cradle-to-grave" LCA process was used for determining the environmental impacts and benefits of infrastructures and technologies employed in the green building retrofit and building FEW system. Between the three LID technologies, the green roof/ vegetable garden produced the lowest carbon emissions and smallest water footprint, followed by the wet detention pond (Table 5). Surprisingly, the greenhouse obtained the highest carbon and water footprints, which can be attributed to the high impact of the concrete material. Nevertheless, a "cradle-to-grave" LCA study performed on LIDs in Ontario determined that, from the total environmental impact assessment, 50% of the environmental impacts (e.g., fossil fuel emission, ozone depletion, and global warming) were from manufacturing, construction, transportation, and decommission phases, and the other 50% were related to maintenance and operation (Bhatt et al., 2019). Therefore, the environmental impacts of LID implementation are minimal in comparison to the acquired advantages.

3.5. Environmental sustainability and community resilience assessment

An annual self-sustainment ratio, *SS*, of 14.09 was determined for a

Table 4
Results from SDM for Student Union.

Month	Tomato[1] (kg)	Tomato[2] (kg)	Lettuce[2](kg)	Energy Demand (kWh)	Filtration (L)	ET[3] (L)	Tomato Irrigation[1] (L)	Lettuce Irrigation[2] (L)	Tomato Irrigation[2] (L)
January	0.00	0.00	0.00	691.15	0.00	0.00	0.00	0.00	0.00
February	0.00	0.00	0.00	691.15	378.46	$3.61(10)^3$	$2.00(10)^4$	$2.00(10)^4$	0.00
March	0.00	0.00	0.00	691.15	567.46	$4.54(10)^3$	$2.04(10)^4$	$2.04(10)^4$	$2.02(10)^4$
April	93.41	27.89	1.99	691.15	662.30	$5.53(10)^3$	$2.06(10)^4$	$2.06(10)^4$	$2.04(10)^4$
May	93.41	27.89	0.00	691.15	454.15	$6.42(10)^3$	$2.07(10)^4$	$2.07(10)^4$	$2.05(10)^4$
June	93.41	27.89	0.00	691.15	624.46	$6.63(10)^3$	$2.05(10)^4$	$2.05(10)^4$	$2.03(10)^4$
July	46.71	13.95	0.00	691.15	851.53	$7.11(10)^3$	$2.06(10)^4$	$2.07(10)^4$	$2.05(10)^4$
August	0.00	0.00	1.99	691.15	870.46	$7.75(10)^3$	$2.09(10)^4$	$2.09(10)^4$	$2.07(10)^4$
September	0.00	0.00	0.00	691.15	813.69	$7.43(10)^3$	$2.09(10)^4$	$2.09(10)^4$	$2.07(10)^4$
October	0.00	0.00	0.00	691.15	756.92	$6.41(10)^3$	$2.08(10)^4$	$2.09(10)^4$	$2.06(10)^4$
November	93.41	27.89	0.00	691.15	529.84	$5.64(10)^3$	$2.08(10)^4$	$2.08(10)^4$	$2.06(10)^4$
December	93.41	27.89	1.99	691.15	264.92	$3.91(10)^3$	$2.05(10)^4$	$2.06(10)^4$	$2.04(10)^4$
Total	513.76	153.4	3.98	$8.29(10)^3$	$6.77(10)^3$	$6.50(10)^3$	$2.27(10)^5$	$2.27(10)^5$	$2.05(10)^5$

[1]rooftop garden,.
[2]greenhouse,.
[3]evapotranspiration.

population of 500 people who are supported by the crops harvested on the rooftop. This suggests the sufficiency of a food supply from a building-scale FEW system to sustain the residents, thus providing self-sufficiency of food to improve community resilience. In further analyses, other indicators related to food security, such as food consumption score, food energy shortfall, food expenditure share, and asset depletion indicator, can be calculated accordingly. Environmental sustainability indicators, such as the carbon and water footprints of each scenario, can be generated as well. The lowest carbon footprint was found for Case 1 (original design), followed by Case 2, which included only the rooftop farming (original design) (Table 6). A larger carbon footprint was determined for the green roof, greenhouse, and renewable energy (Case 3). This observable difference between Case 2 and Case 3 can be attributed to the GHG emissions corresponding to the LCA of wind and solar technologies. Further, the need for regional scale irrigation and fertilization related to crop production can contribute to carbon emission generation, as irrigation contributed to 2.8%−26.6% of GHG emissions in tomato production in Florida, and nitrogen fertilizer use constituted between 17.7%−22.8% of GHG emissions in tomato production in Florida (Jones et al., 2012).

Despite Case 1 resulting in the lowest water footprint from the three cases, the local impact in water consumption can be reduced from the implementation of the green roof and stormwater reuse and recycle. Water consumption can be decreased with the reuse of stormwater for crop irrigation, which enables a closed loop system for irrigation water supply that eliminates the need for a potable water supply. Lastly, the energy supply reliability ratio (r_{es}) (Zhang et al., 2020b) indicating an energy supply resilience of 0.98 was obtained for all cases (Table 7). The energy supply reliability ratio was the highest for the green energy harvesting in the case of the inclusion of wind and solar power, as well as the green roof for rooftop farming.

Finally, the ecological footprint was calculated for the three cases of building retrofit (Table 8). The yield and equivalence factors pertaining to the different land use categories were obtained from the Global Footprint Network data (Global Footprint Network, 2019) (Table S15). To determine the forest footprint, it was assumed that an area from a tropical forest was cleared for coal production. For the calculation of the cropland footprint, the crops were selected as lettuce and tomato. Thus, the ecological footprints for Case 1, Case 2, and Case 3 were determined as 0.134 ha, 0.542 ha, 6.50 ha, respectively. The larger ecological footprint of Case 3 in comparison to Case 1 and Case 2, is related to the carbon footprint value previously determined, since this variable is part of the calculation of the ecological footprint. However, benefits can be expected from the designs in Case 2 and 3. The rooftop urban farming allows for production and supply of locally sourced food, which can affect carbon, water, and ecological footprints by lowering the carbon emissions associated with the energy demand, contributing to heat mitigation (i.e., mitigation of urban heat island effect), decreasing transportation for food imports, reducing water consumption through stormwater reuse, and using less land via the utilization of existing building infrastructures. Further, nutrient retention was demonstrated numerically through the capacity for the green roof/vegetable garden to recycle nitrogen and phosphorus from the green sorption media, thereby improving stormwater runoff quality.

3.6. Multicriteria decision making analysis

Decision making parameters such as the carbon, water, and ecological footprints, energy supply resilience, and food security can be grouped together for an all-inclusive decision analysis. The building retrofit option with the least environmental impact (e.g., water, carbon, and ecological footprint) and greater resilience characteristics (energy supply resilience and food security) is ideal due to its co-benefits. TOPSIS selects the alternative that has the shortest Euclidean distance from the positive ideal solution (S_i^+) and the longest distance from the negative solution (S_i^-) by first constructing a normalized decision matrix, and then a weighted normalized matrix (Jahanshahloo et al., 2006). Our TOPSIS gave equal weight to the carbon and water footprints, energy supply resilience, food security, and ecological footprint due to its local-scale assessment (Table 9). Varying such weights enables the

Table 5
LCA Outcome for a Green Building based on 100-year Life Span.

	Processes	Material	Carbon footprint (kg CO_2-eq)	Water footprint (m^3)
Green Roof	Production/ Extraction	PVC	2.77	1.48
		Polypropylene sheet	68.1	25.2
		Polystyrene	464	372
		Gravel (100 mm)	46.5	699
		Sand (100 mm)	3.94	58.5
		Expanded clay *	1930	324
	Transportation	Road (50 km) ‡	100	6.14
	Energy	Coal	4.25	0.128
		Gas	66.3	11.9
		Oil	7.40	334
	Processing	Thermoforming with calendering	113	290
	Waste Disposal	Landfill for inert materials	46	0.965
		Total	**$1.02(10)^4$**	**$2.12(10)^3$**
Wet detention pond	Production/ Extraction	Polyethylene (LLDPE) granulated*	15,500	1360
		sand	154	2290
		Expanded clay	44,300	7,350
		Gravel	5,400	81,100
	Transportation	Road (50 km)‡	9,780	546
	Energy	Coal	415	12.5
		Gas	7,880	1,420
		Oil	106,000	4,790
	Processing	Thermoforming with calendering	6,860	1.36
	Waste Disposal	Landfill for inert materials	3,810	79.8
		Total	**$2.00(10)^5$**	**$1.13(10)^5$**
Greenhouse	Production/ Extraction	Steel rebar*	168	−16.7
		Flat Glass, coated*	915	187
		Concrete block	9,120,000	497,000
	Transportation	Road (50 km)‡	12,200	681
	Energy	Coal	–	–
		Gas	–	–
		Oil	293,000	13,200
	Waste Disposal	Landfill for inert materials	47,800	1,000
		Total	**$9.46(10)^6$**	**$5.12(10)^5$**

*Replacement of material due to data limitations in SimaPro.
‡Transportation for tractor and trailer.

Table 6
Environmental Sustainability Indicators.

Scenario/Case	Carbon footprint (kg $CO_{2\text{-eq}}$)	Water footprint (m^3)
Base (Case 1)	$1.25(10)^6$	$3.35(10)^4$
Rooftop farming‡ (Case 2)	$5.05(10)^6$	$4.48(10)^6$
Rooftop farming + wind + solar* (Case 3)	$6.06(10)^7$	$4.48(10)^6$

‡Green roof and greenhouse.
*mono-Si PV system.

visualization of the trade-offs and priorities among the building retrofit cases given a selected relative importance via differing weighting factors.. A smaller water footprint contributes to the reduction of potable water demand for nonessential uses, demonstrating the impact of the stormwater reuse. On the other hand, a minimal ecological footprint demonstrates the reduced impact of the community on the environment according to the demands; the community resilience can greatly increase in urban areas through energy and food self-sustainment, improving a community's adaptive capacity in a changing environment. Therefore, considering the decision-making parameters in TOPSIS, Case 3 is favored as the best green building retrofit option in a

Table 7
Energy Supply Reliability Results [a].

Scenario	EENS GJ or (kWh)	Total Energy GJ or (kWh)	EENS ratio	Energy supply reliability ratio (r_{es})
Utility Grid+ Base	163.1 ($4.53(10)^4$)	972.0 ($2.70(10)^6$)	1.68 $(10)^{-2}$	0.9832
Wind+ solar+ Base	159.1 ($4.42(10)^4$)	972.0 ($2.70(10)^6$)	1.64 $(10)^{-2}$	0.9836
Utility Grid+ Green roof	162.7 ($4.52(10)^4$)	968.4 ($2.69(10)^6$)	1.68 $(10)^{-2}$	0.9832
Wind+ solar+ Green roof	158.4 ($4.40(10)^4$)	968.4 ($2.69(10)^6$)	1.63 $(10)^{-2}$	0.9837

[a]Results for PV system of 300 W with 70 panels and wind system of 10 kW.

Table 8
Ecological Footprint.

Case/ Scenario	Ecological footprint (ha)				
	Carbon	Cropland	Forest	Build-up land	Total
Base (Case 1)	0.134	–	2.07 $(10)^{-4}$	1.15 $(10)^{-7}$	0.134
Green roof (Case 2)	0.542	5.19 $(10)^{-7}$	2.07 $(10)^{-4}$	1.15 $(10)^{-7}$	0.542
Green roof + wind+ solar* (Case 3)	6.50	5.19 $(10)^{-7}$	2.02 $(10)^{-4}$	1.15 $(10)^{-7}$	6.50

Table 9
TOPSIS Alternative Selection Results.

Building Alternatives	S_i^+	S_i^-	P_i
Case 1	0.241	0.141	0.369
Case 2	0.231	0.142	0.381
Case 3	0.240	0.302	0.557

building-scale FEW nexus (i.e., rooftop farming with wind and solar energy) .

4. Conclusion

Within a building-scale FEW nexus, the integration of LIDs such as green roof (vegetable garden), greenhouse, and wet detention pond, with renewable energy technologies such as PV and VAWT as supplemental energy generation, was explored via simulations to improve food security and energy supply reliability while reducing water, carbon, and ecological footprints. The results from a suite of building retrofit strategies comprising three scenarios demonstrated the application potential of integrated renewable energy and LID technologies for green building retrofit. The energy supply reliability ratio indicated the energy supply reliability via the inclusion of wind and solar power was the highest due to the green energy harvesting and the green roof for rooftop farming (Case 2), as the estimated annual self-sustainment ratio representing food security of 14.02 indicated the sufficiency of a food supply chain from a building-scale FEW system to sustain the residents.

The green building retrofit can provide positive social impacts in the area of social sustainability such as improved quality from green spaces and economic saving from energy generation (e.g. utility vs. renewables) and possible carbon credits. In addition, rooftop farming and even microgrids can be cost-effective and support a circular and sharing economy that is advisable for the building sector in response to climate impacts. However, limitations are tied to economic assessment in terms of cost-effectiveness and the environmental pay-back period. Further, the integration of renewable energy, urban farming, and LID technologies did contribute to the carbon, water, and ecological footprints relative to the base case, thereby indicating the impact of the implementation of retrofit technologies in improving resilience and sustainability. Although the reduction in building energy consumption was minimal, with an energy reduction of 0.15% between Case 1 and Case 2 with the integration of a vegetable garden (green roof), it can be a step toward achieving a carbon negative building. Despite this finding, transitioning toward a carbon negative building would require additional green building strategies.

Various components can be included in a building-scale FEW nexus as a suite of retrofit strategies for improving food, energy, and water security. The building cooling load reduction qualities of green roof can be factored into the energy sector for potential energy savings, as well as reductions in energy demand and carbon emissions. In an FEW nexus, the three sectors of food, water, and energy are interconnected and interrelated, and all directly or indirectly affect one another. The intertwined supply chain and interdependencies in the FEW nexus can be regarded as a circular economy through the utilization of services and by-products from the interactions of the food, energy, and water sectors. Hence, proper building retrofits could have many interwoven pathways to improve resilience and sustainability, which requires further research.

These results can further support the transition of the current applications from a building-scale system to a community-scale cluster in sustainable cities. Future applications for different types of buildings in a community can deepen our understanding, enable comparison, and support decision-making for urban sustainable development on a regional scale. Further, landscape architecture and land use planning are integrated in building design and urban planning, and landscape architecture can be improved with the integration of renewable energy harvesting, building energy balance simulations, green roof, and stormwater management for developing a building-scale FEW framework. This niche prompts consideration of urban planning when contemplating retrofitting rooftops for integration in different FEW systems. While the reduction of GHG emissions has become essential for all production activities with scales in the food, energy, and water sectors, promoting the adequate use of resources in a centralized vs. decentralized governance structure has also become a necessity. Hence, policy making for food, energy, and water security is imperative for transitioning to sustainable development through the integration of green building and landscape ecology design in a building-scale FEW nexus. These sustainability and resilience indicators can be coupled to further realize the essence of green building retrofit based on an FEW nexus approach. Future work may quantify ecosystem services in a community with a much bigger scale that can be examined in terms of: 1) supply of quality food via urban agriculture; 2) mitigation of urban heat island effects through altering surface albedo and increased evapotranspiration; 3) carbon sequestration potential; 4) water conservation via stormwater retention/reuse; and 5) nutrient retention through improved infiltration that in turn reduces runoff and nutrient loss.

5. Credit author statement

Andrea Valencia formulated and calibrated the system dynamics model and carry out the life cycle assessment with sustainability and resilience assessment, Wei Zhang validated the system dynamics model and building energy assessment with the input of renewable energy recovery, Lixing Gu organized the EnergyPlus components to help building energy assessment, Martin Wanielista organized the BMPTRAINS and CSTORM models, and Ni-Bin Chang proposed the integrative modeling framework and index-based sustainability and resilience assessment. All authors joined the writing of this paper.

Declaration of Competing Interest

The authors have no competing interest.

Acknowledgement

The authors acknowledge the financial support of the Grant from the National Science Foundation (Award ID: ICER 1830036) and suggestions in the system dynamics model from Dr. Md. Uzzal Hossain.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2021.105939.

References

Ahamed, S., Sperling, J., Galford, G., Stephens, J.C., Arent, D., 2019. The food-energy-water nexus, regional sustainability, and hydraulic fracturing: an integrated assessment of the denver region. Case Studies in the Environment 3 (1), 1–21.
Al-Tamimi, A., Al-Ghamdi, S.G., 2019. Multiscale integrated analysis of societal and ecosystem metabolism of Qatar. Energy Rep. 6, 521–527.
Architecture 2030, 2020. About zero code. https://zero-code.org/about/. 2020).
Barbosa, G.L., Gadelha, F.D.A., Kublik, N., Proctor, A., Reichelm, L., Weissinger, E., Wohlleb, G.M., Halden, R.U., 2015. Comparison of land, water, and energy requirements of lettuce grown using hydroponic vs. conventional agricultural methods. Int. J. Environ. Res. Public Health 12 (6), 6879–6891.
Baleta, J., Mikulčić, H., Klemeš, J.J., Urbaniec, K., Duić, N., 2019. Integration of energy, water and environmental systems for a sustainable development. J. Clean. Prod. 215, 1424–1436.
Bazilian, M., Rogner, H., Howells, M., Hermann, S., Arent, D., Gielen, D., Steduto, P., Mueller, A., Komor, P., Tol, R.S., 2011. Considering the energy, water and food nexus: towards an integrated modelling approach. Energy Policy 39 (12), 7896–7906.
Bhatt, A., Bradford, A., Abbassi, B.E., 2019. Cradle-to-grave life cycle assessment (LCA) of low-impact-development (LID) technologies in southern Ontario. J. Environ. Manage. 231, 98–109.
Boake, T., Guzowski, M., Wasley, J., 2008. Carbon neutral design project. In: Roaf, S., Bairstow, A. (Eds.), The Oxford Conference: A *Re*-Evaluation of Education in Architecture. WIT Press, pp. 77–81.
Borucke, M., Moore, D., Cranston, G., Gracey, K., Iha, K., Larson, J., Lazarus, E., Morales, J.C., Wackernagel, M., Galli, A., 2013. Accounting for demand and supply of the biosphere's regenerative capacity: the National Footprint Accounts' underlying methodology and framework. Ecol. Indic. 24, 518–533.
Carfrae, J., De Wilde, P., Littlewood, J., Goodhew, S., Walker, P., 2011. Development of a cost effective probe for the long term monitoring of straw bale buildings. Build. Environ. 46 (1), 156–164.
Carruthers, H., 2013. What is a "Carbon Neutral" Building? Light House Sustainable Building Centre Society, pp. 1–6.
Chang, N.-.B., Hossain, M.U., Valencia, A., Qiu, J., Kapucu, N., 2020a. The role of food-energy-water nexus analyses in urban growth models for urban sustainability: a review of synergistic framework. Sustain. Cities Soc. 63, 102486 https://doi.org/10.1016/j.scs.2020.102486.
Chang, N.-.B., Hossain, U., Valencia, A., Qiu, J., Zheng, Q.P., Gu, L., Chen, M., Lu, J.-.W., Pires, A., Kaandorp, C., 2020b. Integrative technology hubs for urban food-energy-water nexuses and cost-benefit-risk tradeoffs (I): global trend and technology metrics. Crit. Rev. Environ. Sci. Technol. https://doi.org/10.1080/10643389.2020.1759328.
Chang, N.-.B., Hossain, U., Valencia, A., Qiu, J., Zheng, Q.P., Gu, L., Chen, M., Lu, J.-.W., Pires, A., Kaandorp, C., 2020c. Integrative technology hubs for urban food-energy-water nexuses and cost-benefit-risk trade-offs (II): design strategies for urban sustainability. Crit. Rev. Environ. Sci. Technol. https://doi.org/10.1080/10643389.2020.1761088.
Chen, H., Hou, H., Hu, H., Shang, Z., Zhu, Y., Cai, H., Qaisar, S., 2018. Aeration of different irrigation levels affects net global warming potential and carbon footprint for greenhouse tomato systems. Sci. Hortic. 242.
Ermolin, M.S., Fedotov, P.S., Ivaneev, A.I., Karandashev, V.K., Fedyunina, N.N., Burmistrov, A.A., 2018. A contribution of nanoscale particles of road-deposited sediments to the pollution of urban runoff by heavy metals. Chemosphere 210, 65–75.
Florentin, Y., Pearlmutter, D., Givoni, B., Gal, E., 2017. A life-cycle energy and carbon analysis of hemp-lime bio-composite building materials. Energy Build. 156, 293–305.
Ghouleh, Z., Guthrie, R.I., Shao, Y., 2017. Production of carbonate aggregates using steel slag and carbon dioxide for carbon-negative concrete. J. CO2 Util. 18, 125–138.
Global Footprint Network, 2019. Global footprint network calculation factors national footprint and biocapacity accounts 2019. https://www.footprintnetwork.org/licenses/calculation-factors-free/.
Goldstein, B., Hauschild, M., Fernandez, J., Birkved, M., 2016. Testing the environmental performance of urban agriculture as a food supply in northern climates. J. Clean. Prod. 135, 984–994.

Grogan, A.E., Mallin, M.A., 2021. Successful mitigation of stormwater-driven nutrient, fecal bacteria and suspended solids loading in a recreational beach community. J. Environ. Manage. 281, 111853.
Guan, X., Mascaro, G., Sampson, D., Maciejewski, R., 2020. A metropolitan scale water management analysis of the food-energy-water nexus. Sci. Total Environ. 701, 134478.
Guta, D.D., Jara, J., Adhikari, N.P., Chen, Q., Gaur, V., Mirzabaev, A., 2017. Assessment of the successes and failures of decentralized energy solutions and implications for the water–energy–food security nexus: case studies from developing countries. Resources 6 (3), 24.
Hang, M.Y.L.P., Martinez-Hernandez, E., Leach, M., Yang, A., 2016. Designing integrated local production systems: a study on the food-energy-water nexus. J. Clean. Prod. 135, 1065–1084.
Hardin, M., 2006. The Effectiveness of a Specifically Designed Green Roof Stormwater Treatment System Irrigated With Recycled Stormwater Runoff to Achieve Pollutant Removal and Stormwater Volume Reduction. Civil and Environmental Engineering. University of Central Florida.
Hardin, M., Wanielista, M., Chopra, M., 2012. A mass balance model for designing green roof systems that incorporate a cistern for *Re*-Use. Water (Basel) 4 (4), 914–931.
Hashemi, S.S.G., Mahmud, H.B., Ashraf, M.A., 2015. Performance of green roofs with respect to water quality and reduction of energy consumption in tropics: a review. Renewable Sustainable Energy Rev. 52, 669–679.
Jahanshahloo, G.R., Lotfi, F.H., Izadikhah, M., 2006. Extension of the TOPSIS method for decision-making problems with fuzzy data. Appl. Math. Comput. 181 (2), 1544–1551.
Jami, T., Rawtani, D., Agrawal, Y.K., 2016. Hemp concrete: carbon-negative construction. Emerg. Mater. Res. 5 (2), 240–247.
Jing, R., Hastings, A., Guo, M., 2020. Sustainable design of urban rooftop food-energy-land nexus. iScience 23 (11), 101743.
Jones, C.D., Fraisse, C.W., Ozores-Hampton, M., 2012. Quantification of greenhouse gas emissions from open field-grown Florida tomato production. Agric. Syst. 113, 64–72.
Kibler, K.M., Reinhart, D., Hawkins, C., Motlagh, A.M., Wright, J., 2018. Food waste and the food-energy-water nexus: a review of food waste management alternatives. Waste Manage. (Oxford) 74, 52–62.
Kosareo, L., Ries, R., 2007. Comparative environmental life cycle assessment of green roofs. Build. Environ. 42 (7), 2606–2613.
Langston, C., 2015. Green Roof Evaluation: a holistic 'long life, loose fit, low energy'approach. Constr. Econ. Build. 15 (4), 76–94.
Leghari, S.J., Buriro, M., Jogi, Q., Kandhro, M.N., Leghari, A.J., 2016. Depletion of phosphorus reserves, a big threat to agriculture: challanges and opportunitites. Sci. Int. 28 (3).
Lin, D., Hanscom, L., Martindill, J., Borucke, M., Cohen, L., Galli, A., Lazarus, E., Zokai, G., Iha, K., Eaton, D., 2018. Working Guidebook to the National footprint accounts: 2016 Edition. Global footprint network, Oakland.
Mitchell, V.G., Deletic, A., Fletcher, T.D., Hatt, B.E., McCarthy, D.T., 2007. Achieving multiple benefits from stormwater harvesting. Water Sci. Technol. 55 (4), 135–144.
Newell, J.P., Goldstein, B., Foster, A., 2019. A 40-year review of food–energy–water nexus literature and its application to the urban scale. Environ. Res. Lett. 14 (7), 073003.
Ntinas, G.K., Neumair, M., Tsadilas, C.D., Meyer, J., 2017. Carbon footprint and cumulative energy demand of greenhouse and open-field tomato cultivation systems under Southern and Central European climatic conditions. J. Clean. Prod. 142, 3617–3626.
NREAL, 2020. NREL's PVWatts Calculator. https://pvwatts.nrel.gov/.
NREL, N.R.E.L., 2020. EnergyPlus. Energyplus.Nets.
Organization, W.H., 2003. Diet, nutrition, and the Prevention of Chronic diseases: Report of a Joint WHO/FAO Expert Consultation. World Health Organization.
Orhon, A.V., Altin, M., 2020. Utilization of Alternative Building Materials for Sustainable Construction, Environmentally-Benign Energy Solutions. Springer, pp. 727–750.
Pirouz, B., Palermo, S.A., Maiolo, M., Arcuri, N., Piro, P., 2020. Decreasing water footprint of electricity and heat by extensive green roofs: case of Southern Italy. Sustainability 12 (23), 10178.
Pittau, F., Krause, F., Lumia, G., Habert, G., 2018. Fast-growing bio-based materials as an opportunity for storing carbon in exterior walls. Build. Environ. 129, 117–129.
Praneeth, S., Guo, R., Wang, T., Dubey, B.K., Sarmah, A.K., 2020. Accelerated carbonation of biochar reinforced cement-fly ash composites: enhancing and sequestering CO2 in building materials. Constr. Build. Mater. 244, 118363.
Rasul, M., Arutla, L., 2019. Environmental impact assessment of green roofs using life cycle assessment. Energy Environ. Res. Energy Rep. 503–508.
Rezaeiha, A., Montazeri, H., Blocken, B.J.E.C., 2020. A framework for preliminary large-scale urban wind energy potential assessment: roof-mounted wind turbines. Energy Convers. Manage. 214, 112770.
Rosegrant, M.W., Cai, X., Cline, S.A., 2020. Water and Food to 2025. International Food Policy Research Institute, IFPRI, International Food Policy Research Institute, IFPRI.
Sailor, D.J., 2008. A green roof model for building energy simulation programs. Energy Build. 40 (8), 1466–1478.
Santamouris, M., 2014. Cooling the cities–a review of reflective and green roof mitigation technologies to fight heat island and improve comfort in urban environments. %J Solar energy 103, 682–703.
Sonne, J., 2006. Evaluating green roof energy performance. Am. Soc. Heating 48 (2), 59–61.
Toboso-Chavero, S., Nadal, A., Petit-Boix, A., Pons, O., Villalba, G., Gabarrell, X., Josa, A., Rieradevall, J., 2019. Towardsproductive cities: environmental assessment of the food-energy-water nexus of the Urban roof mosaic. J. Ind. Ecol. 23 (4), 767–780.
Vijayan, D., Arvindan, S., Janarthanan, T.S., 2020. Evaluation of ferrock: a greener substitute to cement. Mater. Today: Proc. 22, 781–787.
Wang, J.-J., Jing, Y.-Y., Zhang, C.-F., Zhao, .J..-H., 2009. Review on multi-criteria decision analysis aid in sustainable energy decision-making. Renewable Sustainable Energy Rev. 13 (9), 2263–2278.
Wanielista, M., Eaglin, R., 2020. BMP trains 2020. https://stars.library.ucf.edu/bmptrains/26/.
Yaghoobian, N., Srebric, J., 2015. Influence of plant coverage on the total green roof energy balance and building energy consumption. Energy Build. 103, 1–13.
Zhang, K., Bach, P.M., Mathios, J., Dotto, C.B., Deletic, A., 2020a. Quantifying the benefits of stormwater harvesting for pollution mitigation. Water Res. 171, 115395.
Zhang, W., Valencia, A., Gu, L., Zheng, Q.P., Chang, .N..-B., 2020b. Integrating emerging and existing renewable energy technologies into a community-scale microgrid in an energy-water nexus for resilience improvement. Appl. Energy 279.