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Improving Urban Resilience and Sustainability via Multi-Scale Urban Food-Energy-Water-Waste Nexus Analysis

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IMPROVING URBAN RESILIENCE AND SUSTAINABILITY VIA MULTI-SCALE URBAN FOOD-ENERGY-WATER-WASTE NEXUS ANALYSIS

by

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ABSTRACT

Urban sustainable development requires an in-depth and holistic understanding of the complex Food-Energy-Water-Waste (FEWW) nexus facing population growth, climate change, economic development, and pollution control. Following the United Nations (UN) 17 Sustainable Development Goals (SDGs), goal 11 aims for sustainable cities and communities to be resilient, sustainable, and safe cities to achieve social, economic, and environmental sustainability. Explicitly, SDG target 11.3 concentrates on inclusive and sustainable urbanization for sustainable planning and management. As the UN Food System program aims for inclusive, sustainable, and resilient network, promoting sustainable food systems becomes a necessity to echo social, economic, and environmental sustainability. The goal of this study is placed on analyzing sustainability patterns via different types of FEWW nexuses from building to regional scale in urban regions of Orlando and Miami, FL leading to deepen the holistic understanding of urban sustainable development. A series of system dynamic modeling analyses were conducted to create actionable options for mitigating climate change impact, improving carbon emission reduction, enhancing urban farming and green energy harvesting, and promoting carbon neutrality and decarbonization. By examining the governance structure and function of each city, this study generates actionable information by analyzing the distributed production and storage of materials and energy flows into, out of, and within a community/city given their consumption patterns and supply chains associated with various FEWW nexuses. Findings indicate the importance of sustainable technology hub integration via decentralized decision support in different types of urban FEWW nexuses. The two case studies present feasible alternatives via green building retrofit options and urban green infrastructure integration with respect to low impact developments,

renewable energy harvesting, urban farming, and stormwater reuse. This information will be used to understand the role of key technologies in different types of nexuses associated with different urban planning scenarios affecting the final urban sustainable solutions.

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To my family for all their support

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS (or) ABBREVIATIONS

A0	Retrofit alternative 0
A1	Retrofit alternative 1
A2	Retrofit alternative 2
A3	Retrofit alternative 3
A4	Retrofit alternative 4
A5	Retrofit alternative 5
A6	Retrofit alternative 6
P	Potential energy generation from renewable energy (kWh/year)
R	Energy consumption of building (kWh/year)
Q	Energy consumption for FEWW system (food production) (kWh/year)
S	Potential energy savings from FEWW system (kWh/year)
C	Comparative energy analysis for building vs. FEWW system (%)
I/O	Energy input/output
S1	Scenario 1 (equal sustainability scenario)
S2	Scenario 2 (climate prioritization scenario)
S3	Scenario 3 (economic prosperity scenario)
BMPs	Best Management Practices
CF	Carbon Footprint
CO_2	Carbon dioxide
CSEC	Curtis H. Stanton Energy Center

CRI	Crime Rate Index
EEMUF	East End Market Urban Farm
ESI	Energy Sustainability Index
EQIP	Environmental Quality Incentives Program
EU	European Union
EWRF	Eastern Water Reclamation Facility
FCI	Food Consumption Index
FD	Food Desert
FEW	Food-Energy-Water
FEWW	Food-Energy-Water-Waste
FWR	Food Waste Reuse
FSI	Food Security Index
GF	Government Funding
GHG	Greenhouse Gas
GI	Green Infrastructures
GSI	Green Stormwater Infrastructures
HACCP	Hazard Analysis Critical Control Points
IPCC	Intergovernmental Panel on Climate Change

ITC	Investment Tax Credit
LCA	Life Cycle Assessment
LIDs	Low Impact Developments
MCDA	Multicriteria Decision Analysis
MCDM	Multi-criteria Decision Making
NAO	network administrative organization
NRCS	Natural Resources Conservation Service
OCL	Orange County Landfill
OUC	Orlando Utilities Commission
PI	Priority Index
PV	Photovoltaic
RIB	Rapid Infiltration Basin
SDGS	Sustainable Development Goals
SDM	System Dynamic Model
SL	Sea Level
SFS	Sustainable Food Systems
TOPSIS	Technique for order of Preference by Similarity to the Ideal Solution
UF	Urban Farm

UFN	Urban Farming Network
UGI	Urban Green Infrastructures
UI	Unemployment Index
UNCED	United Nations Conference on Environment and Development
USDA	US Department of Agriculture
UGI	Urban green infrastructures
VAWT	Vertical axis wind turbine
WCII	Water Conserv II
WCIIDC	Water Conserv II Distribution Center
WCSWTS	Wide Cypress Swamp Wetland Treatment System
WEFF	Water-Energy-Food
WF	Water Footprint
WRI	Water Resilience Index
WRP	Water Reuse Potential
WTE	Waste to Energy

CHAPTER 1: INTRODUCTION

1.1. Background

1.1.1. Anthropogenic Impact on Urban Regions

According to the United Nations[1] urban expansion is expected to continue with 68% of the world population projected to reside in urban regions providing an additional 2.5 billion people to urban areas by 2050. While the CO_2 emissions related to anthropogenic activities have increased approximately by 50% since the Industrial Revolution[2]. Within urbanization the construction industry represents approximately 40% of global carbon emissions and energy consumption surpassed by residential building accounting account for 65% of global sectoral emissions[2, 3]. Renewable energy is anticipated to be a major partaker in the urban energy system[4] with climate change mitigation schemes include building energy management with emphasis on reduction of Greenhouse Gas (GHG) emissions. Population growth also exacerbates resource demand and depletion, with a further compound effect placed by climate impacts. For example, based on the Intergovernmental Panel on Climate Change (IPCC), in Florida it is anticipated to experience more extreme rainfall events and droughts with 10%-20% rainfall increase projections[5].

The evolution of urban sustainability and urban planning design has occurred to undertake climate change, economy and urbanization. A sustainable development action plan was recognized by the United Nations in the United Nations Conference on Environment and Development (UNCED) in 1992 in Agenda 21[6]. Consequently, the United Nations has established 17 UN Sustainable Development Goals (SDGs), where Goal 11 aims for sustainable cities and communities to be resilient, sustainable, and safe cities to achieve social, economic, and environmental sustainability[7]. While the Sustainable Development Goals (SDGs) in 2015 have been set by the United Nations to realize long-term sustainable development addressing social, economic, and environmental sustainability[8]. Therefore, sustainable infrastructure must address economic, social, and environmental sectors. The optimal allocation of resources is imperative to minimize energy and water sources and maximize food yields. Consequently, food-energy-water (FEW) systems should encompass a synergistic approach that holistically integrates the cross linkages between the resources allocation, environment, urbanization, and the economy. In parallel, urban sustainable indicators assist in evaluating the FEW systems, environmental impacts and facilitate the decision making. These indicators of sustainability assessment include carbon, water and environmental footprints as well as community resilience. Moreover, these indicators help address the interactions between food, energy, and water sectors while reinforcing the applicability of FEW system in urban sustainable development.

1.1.2. Food-Energy-Water and Food-Energy-Water-Waste Nexus

As high population concentration in urbanized regions presents challenges related to the demand and exacerbation of resources, the implementation of Food-Energy-Water (FEW) nexuses are a solution. Sustainable development can be achieved via the application of FEW nexuses that emphases on managing the complexities and synergistic relationship between the food, energy, and water sectors. The urban FEW nexus incorporates the interwoven and interrelated integration of food, water, and energy infrastructure systems with the ultimate goal of self-sustainment[9]. In a FEW nexus, the energy and water consumption and food production are interconnected and interrelated to form energy for food, food for energy, water for energy, energy for water, water for food, and food for virtual water relations. Yet, there is no specific FEW framework that portrays all of the synergistic relations in the system. These nexus frameworks primary focus on food, energy, and water security while promoting sustainability that safeguards against environmental impacts[10]. The most popular nexus approaches concentrate on identifying trade-offs, optimization and enhancing current practices to aid in decision making and address sustainable development[11].

A large increase in research associated with the FEW nexus occurred between 1980-2010[12]. Presently, urban FEW nexuses have been increasingly examined[13] including modeling frameworks [14-16], and case studies with implementations[17-19]. Further, Cai et al.[20] developed an integrated approach for water-energy nexus risk analysis utilizing system dynamic design, Hang et al.[15] designed a local production system for optimization of FEW nexus, and Hussien et al.[21] developed a system dynamic model at a household scale to measure the food waste, water, and energy consumption in FEW nexus. While Yao et al. [22] developed a mathematical model to address the dynamics of local food, energy, and water production in a FEW nexus comprised of wastewater treatment, wheat production, anaerobic digestion, and nitrogen flow.

An additional phase into understanding the synergies in an urban environment, is considering by food-energy-water-waste FEWW nexus. The FEWW nexus is a broader approach taking into consideration waste produced from food, energy or water sectors that has become a key research area. Since a challenge in addressing sustainability is waste production and management, the synergies among the FEWW nexus can address waste associated with production, processing, consumption, and distribution of resources within the system[23]. Moreover, the planning of FEWW nexus in terms of environmental and economic indicators provides a foundation for stakeholder decision making and regional planning[24]. Yet, a missing link is the evaluation of ecosystem impacts to design sustainable FEWW systems[25]. Therefore, it is necessary to include the assessment of environmental impacts such as carbon and water footprint.

1.1.3. Technology Hubs for FEWW system

Technology implementation is a major component in the development of an FEW or FEWW nexus. For example, the integration of stormwater, solar, wind, energy storage and low impact development (LID) technologies can support the nexus infrastructure. The wet detention pond is a common LID technology and watershed management and flood control method designed to attenuating stormwater runoff by storing and collecting runoff[(26)]. Another typical technology is biofiltration systems including biofilters, rain gardens, and bioretention systems employed for stormwater quality and quantity control. The purpose is to enhance and promote nutrient removal in runoff from adsorption, sedimentation, filtration, and biological uptake processed utilizing soils, vegetation, or media mixtures[(27)].

Incorporating an energy storage system with renewable energy technologies allows for the storage of surplus energy generated for future utilization, thus reducing the reliability on the conventional utility power distribution while concurrently enhancing energy resilience. Two types of solar energy technologies include photovoltaic (PV) and concentrated solar power (CSP). A PV system incorporates solar panels in modules with the aim of adsorbing sunlight to generate energy from the solar energy conversion process occurring within the solar cell. Four CSP configurations include parabolic-dish collector (PDC), parabolic-trough collector (PTC), solar power tower (SPT), linear fresnel collector (LFC). There are three types of wind energy technologies differentiated based on their design including vertical axis, horizontal axis, and ducted wind turbines. The most common wind technology is the horizontal axis wind turbine (HAWT) comprised of a shaft and blades positioned at the top of the tower horizontal position to the ground, and a generator[(28)]. Although, there are various configurations for the vertical axis wind turbines (VAWT) in its design the rotor blades and shaft are connected in a vertical orientation close to the ground[29]. Ducted wind turbines (DWT) take advantage upward wind flow entering the duct which is generated from the pressure produced from wind flow around the building. In urban areas, wind turbines are situated at the rooftop to mitigate the impact of turbulence from the interaction of wind interacting with the buildings and the ground[30]. Hence DWT are appropriate for placement on the side of buildings or mounted on the roof a building[31].The most typical energy storage system with the common material being the lithium-ion battery. Battery energy storage system technology can charge or discharge according to the energy generation and utilization.

1.1.4. Governance in FEWW System

Despite the increased awareness of the concept of FEW and FEWW nexus its role in sustainability from its synergies, the integration of governance and policy in the nexus is still emerging. Since policies are established specifically for each sector, challenges arise in the governance structure due to sectoral-based policymaking which provide difficulty in the incorporation of the identified interconnection in the nexus[32]. Hence, sustainability is compromised when trade-offs are preformed given the siloed concept in the food, energy, water, and waste sectors[33]. Where trade-off and synergies across sectors are generally ignored in resource governance[32]. Simultaneous, robust governance of FEW and FEWW nexus is crucial where the synergies are improved via an integrative resource governance[34]. Generally, local governments are the major constituent and institutional actor in a nexus having direct influence on allocation and sustainable resource management via policies and regulations[35]. For example, Märker et al.[36] found after proposing two FEW nexus governance frameworks to address policy implementation that a combination of both frameworks is necessary for an adequate FEW nexus governance. This encompassed a combination between single integrated system and the restructure of existing institutional setting with cross-sectional cooperation at the sectoral level. Hence, in the decision-making arena the selected form of governance should aim to address long-term decisions, network design and present strategic options for integrated resource management[37].

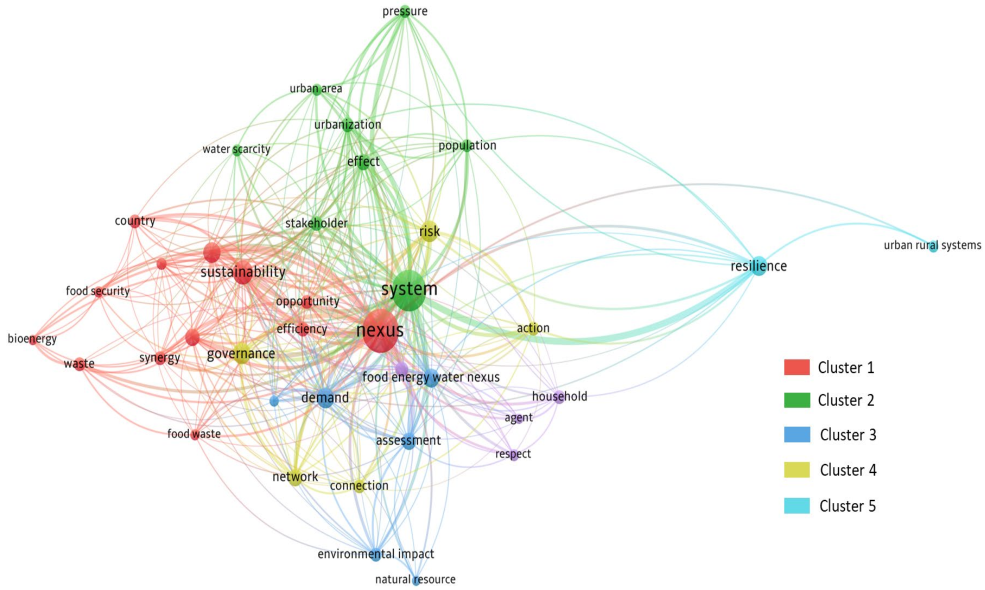
Planning for local food systems is crucial for transitioning and transforming communities towards equity and resilience. The fragmentation of governance and deficiency of investment aggregate to the fragility and vulnerability of critical infrastructure systems[38, 39]. Sequentially, food system planning is a collaborative partnership encompassing the interaction between local and regional governments. Albeit government programs are in place to promote environmental sustainability, these programs oftentimes failed to address social equity[40]. It was discovered by Svara et al.[40] that the assistance to involve low-income households in sustainability and energy programs better provided benefits to the population in need. The formation of policies and stakeholder decision making can be complicated given various decision-making variables, hence promoting decision making strategies in sustainable development. Challenges in the management of natural resources typically arise from not having a consensus in the decision-making process. This can lead to the degradation of natural resources in a highly populated region that relies on policy implementation and planning. Consequently, environmental governance is important when instating a nexus approach as governance can impact nexus implementation[41]. Environmental governance is defined by Lemos and Agrawal[42] as "the set of regulatory processes, mechanisms and organizations through which political actors influence environmental actions and outcomes". Therefore, environmental governance promotes and favors sustainable development in the political, economic, and social aspects[43].

An infrastructure system is essential to provide its service for human sustainment such as water, energy, and transport[38]. However, sustainability have to be incorporated in the governance framework in a circular economy such as the European Union (EU) carbon neutral programs for international trade with its cascade effect. Other EU strategies include the EU Emissions Trading System (ETS) established in 2005, to curtail climate change impacts from GHG emissions[44]. This "Cap and Trade" system related to ETS establishes a carbon market for carbon GHG emission. The EU ETS also provides funding under the NER300 fund to support renewable energy technologies and carbon capture and storage developments.

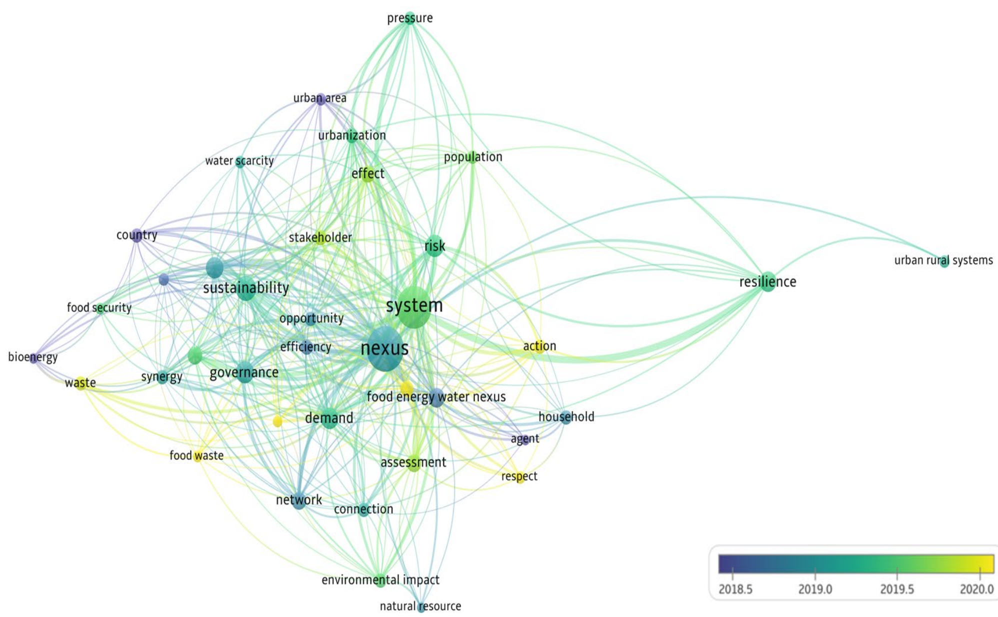
Furthermore, other benefits include the potential of urban agricultural production. Siebert et al.[45] investigated literature of green urban architecture directed at urban food production (e.g., indoor farms, rooftop greenhouses, and rooftop gardens) referred as "ZFarming" or zero-acreage farming, determining the benefits of improved food security, reduction of food miles, and water reuse. Utilizing rooftops for food production can provide a means of food production reducing the impact of land agriculture as according to the Food and Agricultural Organization (FAO) an estimate of around 5 billion hectares of land is allocated worldwide for agriculture, with 1/3 used for crop production[46]. Further, FAO addressed transformation of food systems for food security in the State of Food Security and Nutrition in the World 2021[47]. Further, the American Planning Association focuses of community food system planning directed to improve the food system activities (e.g., production, processing, distribution, and waste management)[48] forming the American Planning Association Food Systems Division (FSD) coalition involving planners and professionals[49].

1.1.5. Meta-Analysis of Nexus Publications

The meta-analysis was performed for peer-reviewed articles public from 2000 through 2022 in the topic of food-energy-water, food-energy-water (FEW), water-energy-food (WEF), and food-energy-water-waste (FEWW) nexus in the Web of Science search engine. Keywords such as "nexus", "urban", and "governance" were used to screen relevant literature published between the timeframes. A total of 339 publications with the topic FEW and keyword "nexus" were published in the categories of environmental sciences, green sustainable science technology, environmental engineering, and environmental studies with the first publication appearing in 2014. Whilst, about 637 publications were published with the keyword "nexus" under the same categories with the first publication appearing in 2012. When expanding the analysis to include literature with additional keywords of "urban" 80 and 69 publications with this topic were published, respectively, for FEW and WEF. Including an additional keywork of "governance" in the literature screening, about 7 and 14 relevant publications were found for FEW and WEF, respectively. Moreover, extending the review of journal and articles in the topic of food-energy-water-waste (FEWW) nexus with the keyword "nexus" a total of 5 publications were published under additional categories like green sustainable science, energy fuels, and chemical engineering with the first publication appearing in 2018. Only one publication was found with the keywords of "nexus" and "urban", with no publications sharing the aforementioned keywords and keyword "governance". The visualization of the network analysis of the co-occurrences of the selected keywords in literature employing VOSviewer provides additional understanding of the meta-analysis (**Figure 1**). The size of the nodes and labels represent the keywords occurrences in the selected publications and color represents the cluster (**Figure 1a**). The curves between the nodes represent the links between cooccurrences and the distance between the nodes depicts relatedness. Cluster 1 represents general topics related to sustainability with keywords such as nexus, synergy, and food security; cluster 2 depicts the topics of urban system with keywords including system, stakeholder, and population. In cluster 3 keywords such as demand, assessment, food, energy, water nexus relate to literature in resource management, and in cluster 4 literature with the keywords governance, risk, network and connection are grouped with more relation towards decision-making assessment. Lastly, cluster 5 represents studies sharing the keywords resilience and urban rural systems with the general topic of resilience with respect to the nexus system and impacts from population. Furthermore, the evolution of keyword occurrences in publications which may relate to the shift in research focus evolved from urban area to sustainability to urbanization to resilience to stakeholder and waste from approximately 2018 to 2020 (**Figure 1b**).



(a)



(b)

Figure 1. Meta-analysis based on co-occurrences of keywords in the literature using VOSviewer.

(a) network visualization and (b) average publication year.

1.2. Study Objectives

It is critical to address sustainable development, specifically urban expansion understanding that food is a necessity and an essential for human sustainment along with water and shelter. Food, energy, water and waste are intertwined and thus the sustainability approach should aim for a reliable, resilient and cost-effective infrastructure for FEW and FEWW systems. Urban farming and urban agriculture practices can provide food security and alternative food production in urbanized region aimed for community self-sustainment. This can be implemented in buildings or infrastructures in high-density urban cities and coupled with sustainable practices, thus promoting suitability. The focus of this study has been placed in the urban region, where resource management is crucial given the high population densities in metropolitan regions which consequently affects and alters land use. The goal in the progression of the four cases presented is to address land management, climate change impact from extreme rainfall events and droughts, and observe the sustainable transition of the nexus. This study aims to provide a foundation for planning, design, and decision support for stakeholders with evaluation of scenarios considering existing urban infrastructure and importance of urban agriculture with support of modeling tools.

Chapter 2 touches upon urban sustainability with rooftop farming, stormwater reuse, renewable energy, and low impact development (LID) at a building-scale FEW nexus at the University of Central Florida located in Orlando, FL. Considering the existing building structure, the case study focuses on evaluation of various green building retrofit strategies in an integrative building-scale food-energy-water (FEW) modeling framework. Renewable energy generation from solar photovoltaic (PV) and wind energy from vertical wind axis turbines (VAWT) are highlighted, in congruency with urban agriculture from green roof (vegetable garden) and greenhouse employing stormwater reuse for irrigation. Coupling system dynamic modeling

(SDM) expansion of the continuous stormwater treatment outflow model (CSTORM) in the visualization of stocks and building energy flows with life cycle assessment (LCA) to determined climate impact associated with greenhouse gas (GHG) emissions the retrofit alternatives can be evaluate with respect to carbon and water footprints, energy supply resilience and food security. With these environmental sustainability indicators, stakeholder decision making process for planning can be simplified by multicriteria decision making analysis (MCDM) to make distinction between retrofit alternatives with respect to stakeholder's most significant criteria.

Chapter 3 transitions to community-scale food-energy-water-waste (FEWW) system in Baptist Hospital Miami, FL accentuating the large energy consumption by the building sector. In this case study, building retrofit strategies pertaining to renewable energy generation are evaluated within the FEWW system. Urban agriculture as in a green roof (vegetable garden), stormwater reuse, and renewable energy generation from solar, wind and waste-to-energy technologies are assessed. A system dynamics analysis is conducted to determine in congruency with building and FEWW system energy assessment to assessed building energy retrofit strategies and decarbonization pathways in a community-scale FEWW Nexus.

Following the expansion of urban sustainability and understanding the importance of interconnection and interdependencies amongst the food, energy, water, and waste sectors, Chapter 4 focuses in the assessment of an urban FEWW in Orlando, FL exploring the synergies among agents in the nexus in the regional level analysis across a various of planning alternatives associated with food insecurity and climate impact. It aims to highlight, urban sustainability by urban agriculture, the co-benefit of utilizing reclaimed water and stormwater for potable water reduction and address many resource links in the waste sector in the proposed FEWW nexus.

To culminate the urban sustainability evaluation, an urban farming network consists of 23 urban farms situated in greater Miami area are selected in Chapter 5 to observe the dynamics of a scaling-up approach. The three aspects of sustainability (social, environmental, and economic) are integrated in a clustering analysis and multicriteria decision making analysis to rank the clusters based on priority index (PI) to visualize the urban farms that require higher priority. Further, to echo stakeholder involvement and aid in decision making the three present scenarios of the scaling-up are assessed to help pinpoint for which scenario to plan or follow for clustering. Lastly, governance and policy are explored with respect to the food system, water and energy management

CHAPTER 2: SYNERGIES OF GREEN BUILDING RETROFIT STARTEGIES FOR IMPROVING SUSTAINABILITY AND RESILIENCE VIA A BUILDING-SCALE FOOD-ENERGY-WATER NEXUS[1]

2.1. 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(50). 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(51). These alternative building materials include bio-based materials like those that are hemp-based(52), straw-based (51, 53), and bamboo-based(54), all of which are natural renewable resources(55). Concrete(3, 56), ferrock(57), and fly ash(58) 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(59). As part of the initiative from Architecture 2030, the global building energy standard ZERO Code calls for zero-

[1] Authors: Valencia, A., Zhang, W., Gu, L., Chang, N.B. and Wanielista, M.P., 2022. Synergies of green building retrofit strategies for improving sustainability and resilience via a building-scale food-energy-water nexus. Resources, Conservation and Recycling, 176, p.105939.

net-carbon buildings through onsite/offsite renewable energy and cost-effective and efficient construction(60).

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 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(61). Many recent studies have sought to promote sustainability through the implementation of FEW nexus analyses(13, 15, 18, 35). Jing et al.(62) 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.(19) 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(13), ranging from case studies and implementations(17-19) to various modeling frameworks(14, 15, 63). 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(64).

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(61). 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(14, 61, 65, 66). 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 chapter 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(67), the continuous stormwater treatment outflow model (CSTORM)(68), 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.

2.2. Methodology

2.2.1. Background

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) (**Figure 2**).

Figure 2. Student Union rooftop farming with a green energy harvesting (solar PV and wind turbine system) and stormwater reuse plan

2.2.1.1. 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 into 148.6 m^2 (1,600 ft^2) for food production. The roof-top 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 for green energy harvesting. Solar energy harvesting is employed over an area of 153 m^2 (1,6470 ft^2), located on the other half of the roof, while 153 m^2 (1,6470 ft^2) of the ground area adjacent to the building is proposed for VAWTs. **Figure 3** 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.

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 (37 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

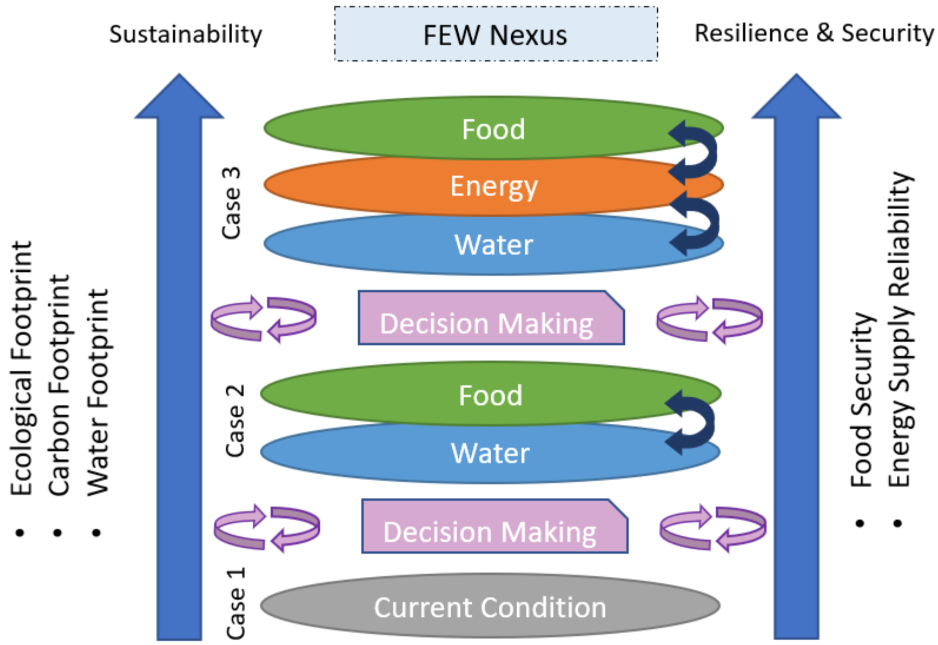


Figure 3. Schematic flow of transition of FEW nexus implementations in case studies (scenario setting)

2.2.2. 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(9), facilitating the development of an urban FEW system. Given the decrease in potable water sources, stormwater has become a valuable resource. Stormwater harvesting encompasses the collection of runoff (e.g., overland flow) produced from rainfall events via vegetated systems, including bioretention and swales, and drainage systems such as pipe/channel networks(69).

However, urban runoff contributes significantly to heavy metals (Cu, Pb, Ni and Zn)(70), suspended solids, and nutrient (nitrogen and phosphorus) pollution(71), 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(72). 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(73).

Apart from being an integral part of an LID, green roofs have also been explored for reducing energy(74), carbon emissions(75), and heat island effect in urban areas, and are thus an option for sustainable building retrofit(76). 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(77). Sonne(78) 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(79).

The 148.6 m^2 (1,600 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(79). Additionally, a green roof model for energy simulation was created by Sailor(74) to determine the energy savings from EnergyPlus. 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(80). The study determined a positive correlation between increased plant coverage and reduction in surface temperature, attributed to the decreased absorption of solar radiation.

2.2.3. Integrative Modeling Framework for a Building-scale FEW nexus

2.2.3.1. 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 was developed Hardin et al.(68) 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(68, 79), 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(81) for LIDs implementation (**Figure 4**). 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 in Valencia et. al. (82). 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(82), 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 vertical axis wind turbine (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(83). 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(65, 66). The method for calculating the solar PV energy generation according to the PVWatts calculator(84) 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(82) (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.

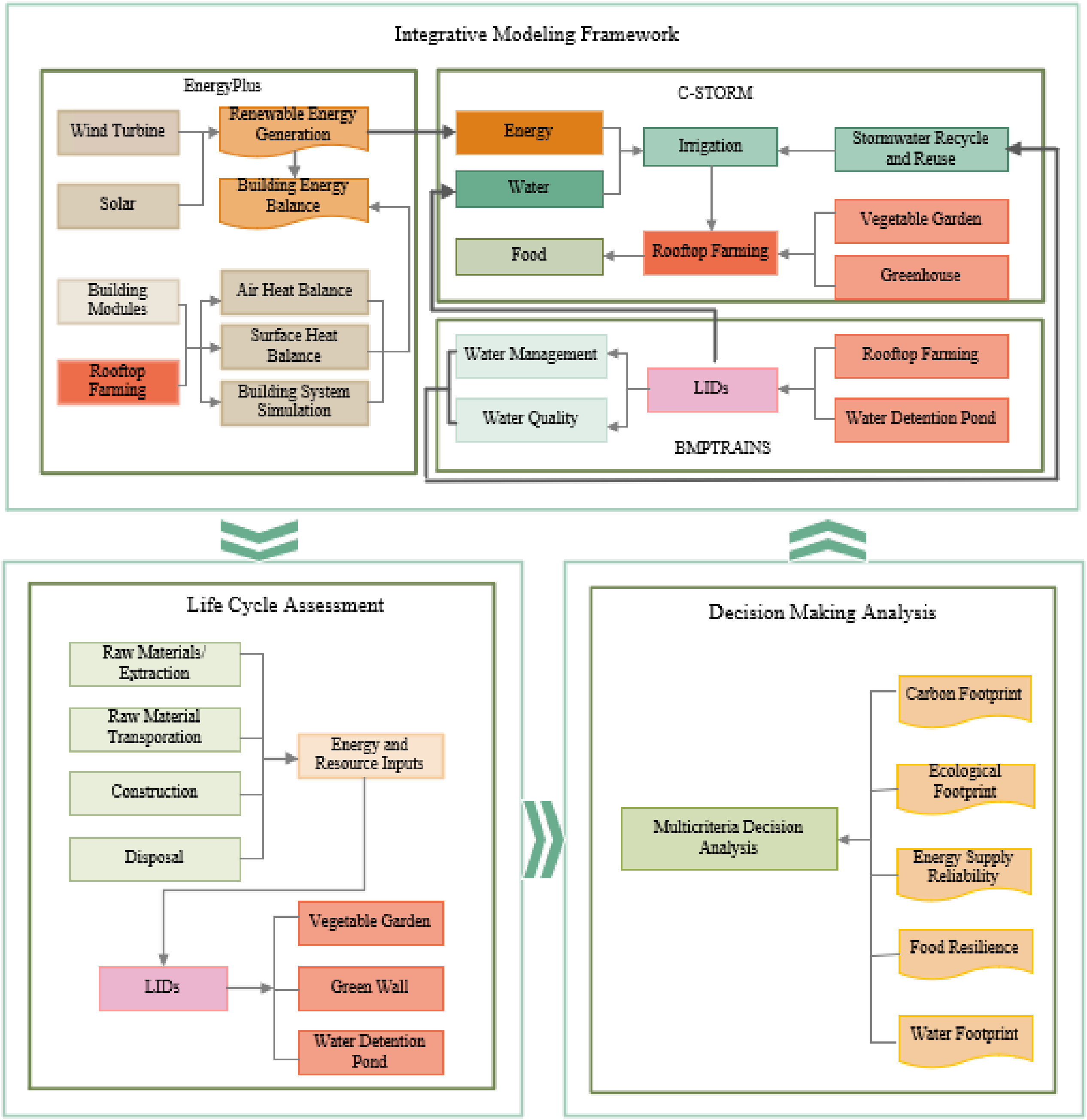


Figure 4. Data Modeling Framework and Assessment Strategy (including green error from decision making using CSTORM)

2.2.3.2. 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 roof-top-farming system with solar PV and VAWT (**Figure 5**). The water balance, encompassing the green roof, cistern storage, and wet detention pond, is described in Supplementary Information[82] 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 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 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[82].

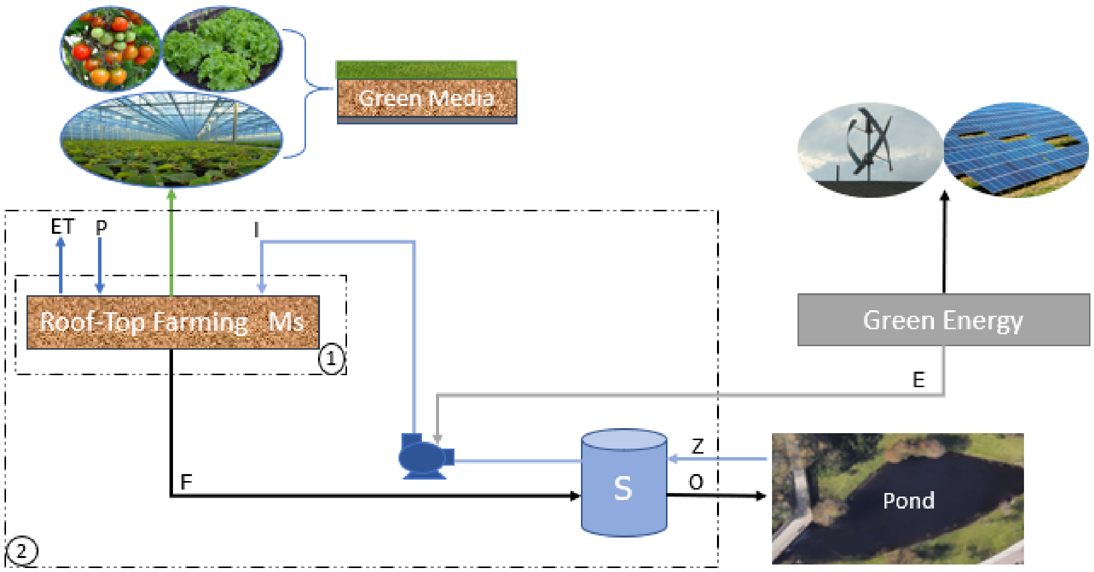
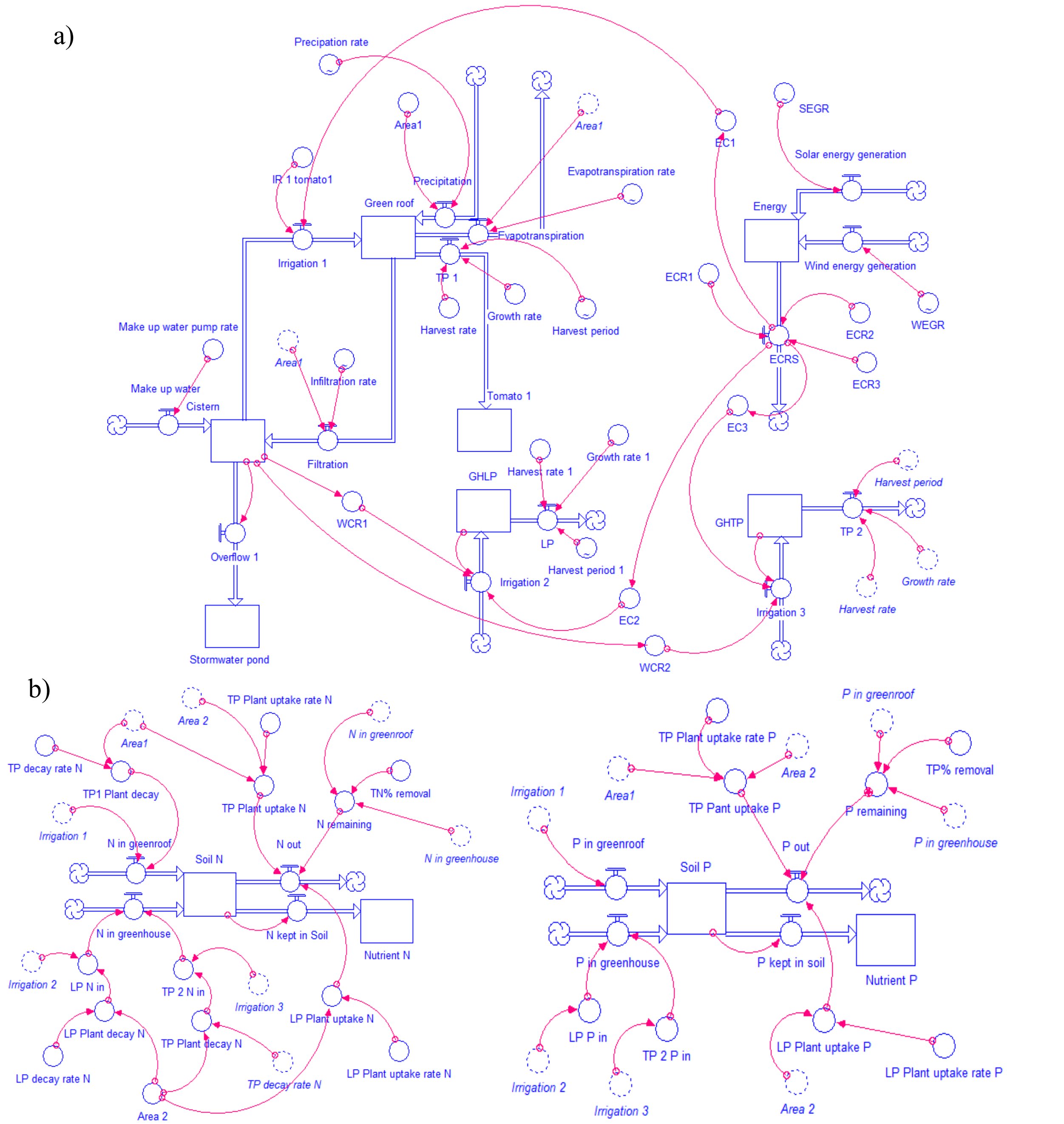


Figure 5. Expanded CSTORM SDM for green building design. Dash boxes represent mass balance boundaries.

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. (85)
Tomato 2 (greenhouse)	5.95 L/kg[b]	9.18 kWh/kg[a]	9.8 kg/m^2-yr[a]	[a]Goldstein et al. (85) [b]Ntinas et al. (86)
Lettuce (greenhouse)	20 L/kg[c]	148.57 kWh/kg[a]	0.7 kg/m^2-yr[a]	[a]Goldstein et al. (85) [c]Barbosa et al. (87)

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 **Figure 6** exhibits the integrative modeling framework



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

Figure 6. (a) Expanded CSTORM SDM for Green Building Design with Green Roof, Solar PV, and VAWT System; (b) Nitrogen and Phosphorus cycling in the roof-top soil

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)	2,649	2,721
February	35.56 (1.40)	47.24 (1.86)	7.62 (0.30)	2,464	2,528
March	45.72 (1.80)	43.75 (2.51)	8.89 (0.35)	3,239	3,366
April	48.01 (1.89)	77.72 (3.06)	6.10 (0.24)	3,378	3,251
May	113.79 (4.48)	90.42 (3.56)	8.38 (0.33)	3,390	2,366
June	311.40 (12.26)	87.88 (3.46)	11.43 (0.45)	2,952	1,804
July	159.26 (6.27)	102.85 (4.05)	11.68 (0.46)	3,006	1,909
August	330.96 (13.03)	105.66 (4.16)	10.92 (0.43)	2,975	1,301
September	75.69 (2.98)	87.88 (3.46)	10.16 (0.40)	2,753	2,576
October	144.27 (5.68)	80.26 (3.16)	7.12 (0.28)	2,920	2,351
November	33.78 (1.33)	53.09 (2.09)	3.56 (0.14)	2,558	1,618
December	81.79 (3.22)	45.47 (1.79)	4.83 (0.19)	2,370	2548

*EnergyPlus PV generation results

2.2.4. 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[88-91], with some studies examining the water footprint reduction[91] and water quality and energy consumption from green roof[92]. 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 8,652 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 regard 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 **Figure 7**.

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[82]. 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)[93]. 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).

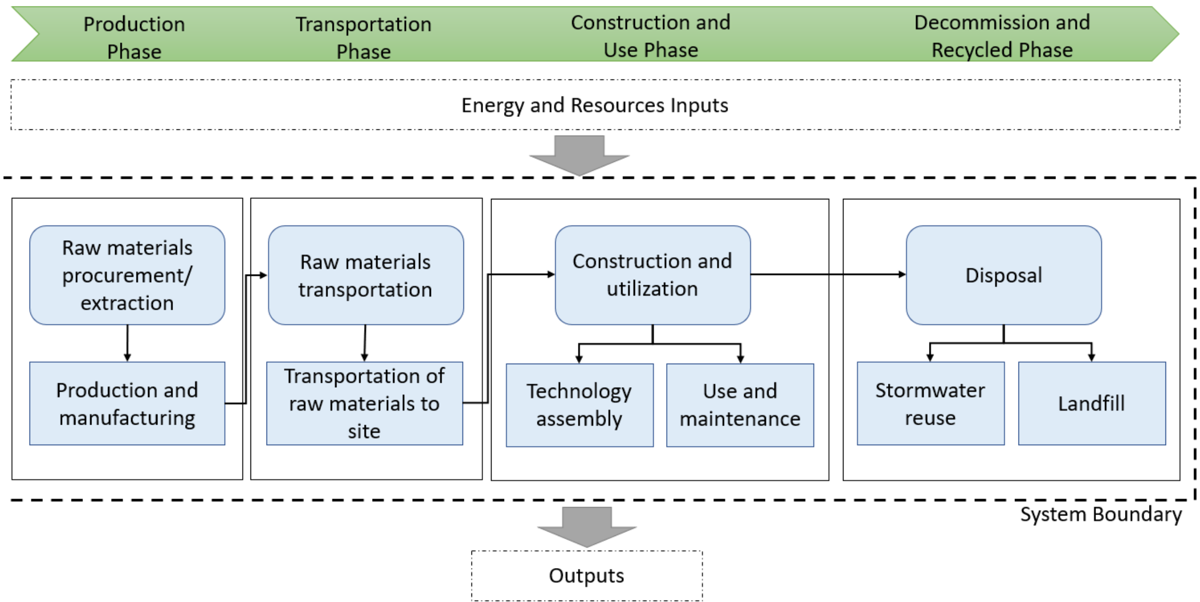


Figure 7. LCA analysis for LID (green roof and wet detention pond) and greenhouse process schematic

2.2.5. 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[82].

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

Here $CO_{2_{footprint}}$ = carbon footprint in kg, $CO_{2\text{-eq}}$, $CO_{2_{utility}}$ = $CO_{2\text{-eq}}$ emission for the utility grid for energy generation (e.g. carbon and natural gas), $CO_{2_{Ren.\ energy}}$= $CO_{2\text{-eq}}$ emission from renewable energy (PV and VAWT), $CO_{2_{technologies}}$= $CO_{2\text{-eq}}$ emission for green building retrofit technologies (e.g. LIDs and greenhouse), and $CO_{2_{crop,local}}$ = $CO_{2\text{-eq}}$ 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 generation (Eq. (2)). The water consumption values utilized in the analysis that are extracted from literature are described in S 2.3[(82)].

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

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))[(94)].

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

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))[95]:

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

where 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 in Valencia et al. [82], acquired from literature, and LCA into STELLA SDM, as visualized in **Figure 8**.

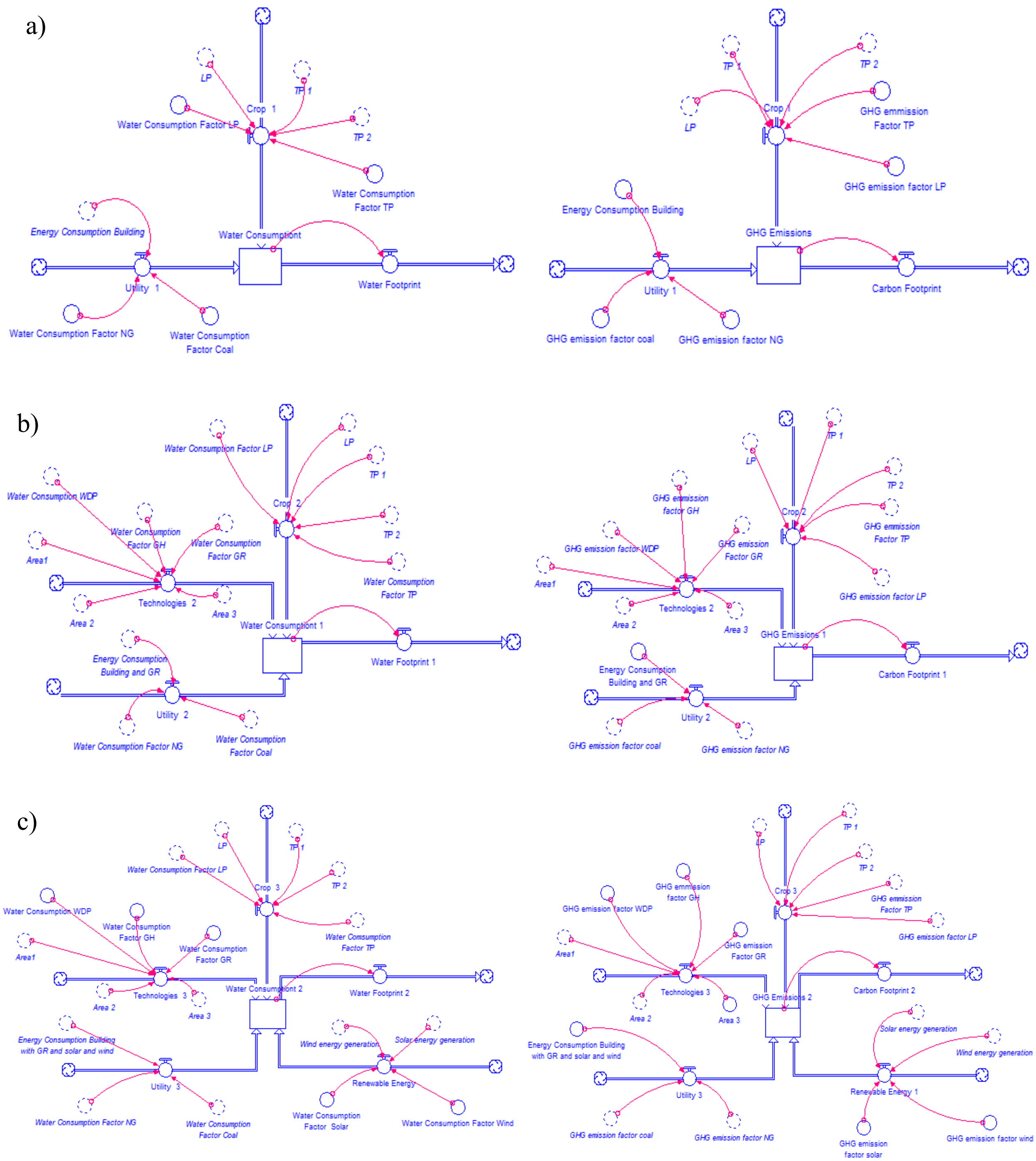


Figure 8. SDM for water and carbon footprint calculations for a) case 1, b) case 2, and c) case 3

2.2.6. 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. (5)). 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[96] was used for food resilience assessment.

$$SS = \frac{F_{produced}}{F_{consumed.}} \tag{5}$$

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:

$$r_{es} = \frac{EENS}{E_{total}} \tag{6}$$

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 (8,760 hours). 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[82]. MTTR is a basic measure of the maintainability of repairable items[64].

2.2.7. 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[97]. The description of TOPSIS methodology is explained in Supplementary Information S 2.5[82] (Eq. S19-25). 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%.

2.3. Results and Discussion

2.3.1. Green Energy Harvesting

The total energy generation from solar PV and wind VAWT was simulated in EnergyPlus for an area of 153 m^2 (1,650 ft^2) in Orlando, Florida. The total annual solar PV energy generation was determined as 124.92 GJ (3.47 x 10^4 kWh), or a monthly average of 10.4 GJ (2.89 x 10^3 kWh). Additionally, the total annual wind energy generation was modeled as 101.9 GJ (2.83 x 10^4 kWh), or a monthly average of 8.50 GJ (2.36 x 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 fed 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(64). 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.

2.3.2. 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 x 10^4 GJ (5.93 x 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 x 10^4 GJ (2.81 x 10^6 kWh). The electric, gas, and cooling consumptions were simulated as 9.71 x 10^3 GJ (2.70 x 10^6 kWh), 417.60 GJ (1.16 x 10^5 kWh), and 1.45 x 10^3 GJ (4.03 x 10^5 kWh), respectively. However, a discrepancy was observed when comparing estimates with the annual building energy demand of 2.13 x 10^4 GJ (5.93 x 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, so climate differences may also to contribute 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)[(82)]. 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.

2.3.3. 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), which corresponds to the appropriate time required for vegetable seeds to germinate (**Table 4**), 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 $kg^{\bullet}yr^{-1}$) cultivated via the green roof in comparison to the greenhouse (153.4 $kg^{\bullet}yr^{-1}$). While a total of 691.15 kWh per month or 8,294 $kWh^{\bullet}yr^{-1}$ 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.

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

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[98]. 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 1,175 $kg{\cdot}yr^{-1}$ of nitrogen (82%) and 52 $kg{\cdot}yr^{-1}$ of phosphorus (42%) for crop growth (Table S14)[82]. 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 roof-top 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 $kg{\cdot}yr^{-1}$ and 0.08 $kg{\cdot}yr^{-1}$, 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 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.

2.3.4. 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[(88)]. Therefore, the environmental impacts of LID implementation are minimal in comparison to the acquired advantages.

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	7.4000	334
	Processing	Thermoforming with calendering	113	290
	Waste Disposal	Landfill for inert materials	46	0.965
		Total	**$1.02(10)^4$**	**$2.12(10)^3$**

	Processes	Material	Carbon footprint (kg CO_2-eq)	Water footprint (m^3)
Wet detention pond	Production/Extraction	Polyethylene (LLDPE) granulated*	15500	1360
		sand	154	2290
		Expanded clay	44300	7350
		Gravel	5400	81100
	Transportation	Road (50 km)ˡ	9780	546
	Energy	Coal	415	12.5
		Gas	7880	1420
		Oil	106000	4790
	Processing	Thermoforming with calendering	6860	1.36E+04
	Waste Disposal	Landfill for inert materials	3810	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	9120000	497000

Processes	Material	Carbon footprint (kg CO_2-eq)	Water footprint (m^3)
Transportation	Road (50 km)ⱶ	12200	681
Energy	Coal	--	--
	Gas	--	--
	Oil	293000	13200
Waste Disposal	Landfill for inert materials	47800	1000
	Total	**9.46(10)^6**	**5.12(10)^5**

* Replacement of material due to data limitations in SimaPro

ⱶ Transportation for tractor and trailer

2.3.5. Environmental Sustainability and Community Resilience Assessment

An annual self-sustainment ratio, SS, of 14.09 was determined for a population of 500 people who are supported by the crops harvested on the roof top. 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[(99)].

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

Despite Case 1 resulting in the lowest water footprint from the three cases, the local impact in water consumption can 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})[64] 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.

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 300W with 70 panels and wind system of 10kW

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[100] (Table S15[82]). 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.

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

2.3.6. 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[101]. 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 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 building-scale FEW nexus (i.e., rooftop farming with wind and solar energy) (Table S11) [82].

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

2.4. Final Remarks

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 roof-top 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. Moreover, the water footprint was lower when implementing building retrofit (Cases 2 and 3).

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. As observed in this study, the inclusion of renewable energy can further promote reduction in carbon emissions if coupled with a green roof. 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 retrofit transition 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.

CHAPTER 3: BUILDING ENERGY RETROFIT STRATEGIES AND DECARBONIZATION PATHWAYS IN COMMUNITY-SCALE FOOD-ENERGY-WATER-WASTE NEXUS

3.1. Introduction

Building sectors including building construction are responsible for consuming 36% of the total global energy consumption[102]. Depending on the regions, about 20-25% of the total urban area is covered by building roofs, and the temperature of the outer surface of roofs can easily increase to 50–60° C due to solar heat gain which foster indoor thermal[103]. It causes an increase in cooling requirements of buildings in metropolitan regions due to the absorbed solar radiation by the urban materials that dissipate to the atmosphere[104, 105]. Buildings are also a major contributor to substantial global greenhouse gas (GHG) emissions as it accounts for about 40% of the total direct and indirect emissions due to its extensive energy requirements[102]. Such emphasis has been increasing due to the agenda to mitigate climate change globally, specifically carbon emission reduction, carbon neutrality, and decarbonization by organizations such as the United Nations in the COP26 summit[106] and European Climate Law[107]. To achieve the net zero emissions and decarbonization agenda, new technology and technology investment and transition to clean energy via the reduction of cost for clean energy technology has been discussed in COP26[108]. Additionally, the role and importance of governance structure in critical infrastructure systems (such as the ones that provide essential services) that align with the Coalition for Disaster Resilient Infrastructure priorities has received wide attention to improve urban resilience to climate change Kannan et al.[38]. Retrofitting existing buildings, especially the building envelope can provide considerable opportunities to reducing its energy consumption and subsequent GHG emissions[109]. Whilst green energy technologies aid in the GHG emissions reduction, coupling green energy technologies with green infrastructure retrofit solutions by a nexus approach at the community scale can be a feasible and promising strategy.

Several previous studies focused on green roofs and its influences on building energy performance and urban temperature reduction[110-114] using different energy models, such as EnergyPlus[110, 112, 115, 116], MIT Design Advisor[117], transient building simulation program (TRNSYS)[118, 119], ESP-r[120], and WUFI[121], and Envi–MET model[122, 123]. However, the validation of those models using whole-building energy data or at larger scales with real-world application is very limited[124]. Energy models in a building scale can support the city managers in a decision making process to evaluate, analyze, and prioritize energy conservation measures for mitigation investment, design incentives, rebate programs, and so on in the urban areas[125, 126]. Eco-city planning with landscape design, green covers, and lower bound buildings induced urban cooling effects by reducing air temperature and resulting in decreased building energy demands[127]. Further, energy management has become an emerging issue specifically in the demand-side in line with a changing power grid infrastructure[128], triggered by the concept of energy hub[129]. The concept of community energy management system encompasses the implementation of renewable energy infrastructure such as community energy[4], known as a decentralized system as part of strategic planning for local energy generation and consumption[4]. For example, renewable energy generation management with microgrid is presented with real-time energy management[130]. A salient example of energy management approach is a smart city where the integration and optimization of energy supply is necessary. For example, a basic model for energy management for a smart city with a battery system was demonstrated in Japan by Takanokura et al. [131]. Thus, community energy management can in turn support building energy budget management that involves the cost of power consumption and energy flow incentive programs to aid in cost savings. Moreover, the building-scale solar photovoltaic (PV) system in a building roof could save 23% of the whole building energy consumption in Turkey[132].

Concurrently, an increasing research effort has been directed to synergistically manage food, energy, and water resources simultaneously in a food, energy, and water (FEW) nexus[32, 133]. As these resources are interconnected driven by existing or emerging technologies and varying governance structures, the tradeoffs among these resource sectors have been evolving over time for sustainable development[134, 135]. Nevertheless, several studies focused on different aspects of the development and implementation of a food-energy-water-waste (FEWW) nexus by analyzing the emergent interconnected and interdependent sectors for case-specific applications[13, 136-138]. Tien (139) also argued that building requirements with respect to performance-based resilience in an integrated FEW network are needed to motivate the design of community resilience. This enlargement from a FEW nexus to a FEWW nexus comes with the challenge in combining community design and building architecture, urban planning, and regional economics. Such compounded challenge is phenomenal via the integration of waste sector into the existing FEW nexus, given the various synergies such as the production of renewable energy from anaerobic digestion[140]. As buildings are the central part of resources demand in urban regions, it is thus vital to explore decarbonization pathways in a well-configured urban FEWW nexus. Although the FEWW nexus proposes a promising conceptual framework, the transdisciplinary use of a FEWW nexus approach for urban resilience involves some new philosophical streamlines and its associated engineering design methods are still limited[141]. As technological advancements are moving forward at a rapid pace, the optimal integration of technology hubs via a viewpoint of green engineering has become an indispensable and promising method. Moreover, the separate building retrofit strategies used for building information modeling to characterizes the distinct information pertaining to building planning, design, and management are challenged by smoothly incorporating all aspects simultaneously toward decarbonization in a FEWW nexus.

To bridge the gaps as highlighted in above, this study is aimed to comprehensively evaluate how to enhance the community resilience via building energy retrofits through the application of decentralized decision support in a FEWW nexus with the aid of building energy modeling, urban farming, local waste-to-energy initiative, and low impact development (LIDs). The results can contribute to improve building energy management at a community scale with having potential to be integrated in a microgrid system. The practical implementation of this case-based engineering analysis also leads to compare a few retrofit strategies of a medical center building - Baptist Hospital located in Miami, FL, USA for demonstration(82). Thus, research questions were investigated: i) can the proposed renewable energy technologies sustain the community energy demand with the aid of low impact development, urban farming, local waste-to-energy initiative via a FEWW nexus approach? ii) what is the role of anaerobic digestion system as a local waste-to-energy initiative for renewable energy generation in a FEWW nexus? iii) how does the carbon footprint vary for all the retrofit alternatives? and iv) is there a competitive decarbonization pathway over the alternatives in terms of carbon footprint reduction?

3.2. Background

3.2.1. Integrative Ideas for Building Green Roof Retrofit Potential

Building envelopes including green roofs can significantly improve the indoor air quality and reduce building energy consumption in air-conditioned buildings. Typically, green roofs are placed at the surface of the roofs after slight modification where different types of vegetation/plants are planted on the top of growth medium[142]. The potential reduction of urban heat island was simulated using EnergyPlus software in an air-conditioned building in tropical region where the study found that green roof reduces heat gain by 13.14 kWh•m^{-2} (about 31%) during the summer days[104]. By implementing green roof, the cooling energy savings was 1-11% in a one-story office in different warm European climates, whereas it was up to 7% in cold climates[143]. Additionally, green roof retrofit could reduce building energy demand by 3% with significantly improved indoor comfort in Canada[144].

Comparison to a conventional roof, about 15-51% of urban excess heat was reduced due to the implementation of green roof with sustainable irrigation[145]. Previous work also showed that extensive green roofs save 20% more energy in the Mediterranean climate and saved 24-35% of the building energy requirements in the hot-humid climate[146]. A green roof is able to reduce the number of indoor overheating hours in summer by 98.2% in Italy[147]. Although it could reduce annual energy demand, the level of savings may decrease when green roofs are dry in the summer[148]. Another study showed that about 25% heating and 20% cooling demand can be reduced by adopting green roof in the Mediterranean climate; however it increases the lifetime costs of roof system of the building[149]. Further, the decreasing rate of the annual cooling demand was 13 kWh/m^2 in the plant coverage area[80]. Besides. green roofs can provide ecosystem services, stormwater retention and reductions, thermal insulation, and carbon uptake[150]. Thus, green roofs as a potential urban farming site are considered as one of the sustainable practices to alleviate the adverse urbanization effects leading to enhance stormwater management and effluent water quality, reduce urban heat island, improve building energy consumption, etc.[151], while green roof is also considered as part of LID practices aimed for management in urban stormwater in catchment areas[152], its drawback is toed to additional installation and maintenance costs, energy consumption for irrigation during dry periods, unexpected roof leakage and damage, etc.[124].

In congruence to addressing urban sustainability and resilience in a green, blue and hybrid (meaning green-grey) infrastructure the urban green infrastructures (UGI) are one of the green implementation strategies[153]. UGI include green roofs, bioswales, permeable pavements, land conservation, and stormwater harvesting technologies; yet for infrastructure adaption it is important to consider the optimization of UGI to reduce tradeoffs[153]. UGI can be considered an extension of green infrastructures (GI) proposed for stormwater management strategies[154]. However, infrastructure practices focused on urban stormwater are known as green stormwater infrastructures (GSI) mainly to aid in water quality management and urban farming challenges in regard to regulating the nutrient cycle at the local scale[155].

3.2.2. Study Site

The Baptist Hospital located in Miami, FL is comprised of various medical buildings (including main building, surgery center, medical arts, emergency center), parking lot and garage, and two stormwater ponds. The total estimated rooftop area available for prospective cultivation is 74,431 m^2 (801,170 ft^2) with an approximate flat rooftop area of 39,159 m^2 (421,501 ft^2). For demonstration, one building (Medical Arts Building) is selected as representative for adopting the proposed FEWW system, and for evaluating the influence of FEWW system to the building energy consumption (**Figure 9a**). It is assumed the overall operating hours of these building is 07.30-21.00 from Monday-Friday. The Baptist Hospital Medical Arts Building has a total of 6 stories consisting of 321 windows and 4 main doors with a total roof top area of approximately 1,387 m^2 (14,930 ft^2). As a new green building initiative, the total rooftop area will be divided to incorporate a green roof garden and roof top solar PV panels (**Figure 9b**). In this analysis, the green roof garden with total area of 600 m^2 (6,458.3 ft^2) can be partitioned into a few sections such as 300 m^2 (3,229.2 ft^2) can be used for tomato and cabbage production, one section of the rooftop contains solar PV panels comprising of an area of 490 m^2 (5,382 ft^2). and additional 490 m^2 (5,382 ft^2) may be used for vertical axis wind turbines (VAWT) located adjacent to the building. Floating solar PV panels can also be in the largest stormwater pond (wet detention pond) taking an approximate area of 11,110 m^2 (119,587 ft^2) being 50% of the pond area. The parking lot with an area of 13,120 m^2 (142,083.6 ft^2) and parking garage 4,870 m^2 (52,420 ft^2) may be converted to sustain solar PV systems (**Figure 9c**). Lastly, a small-scale anaerobic digestion system of capacity of 181 m^3 (power capacity 22 kW)[(156)] may be proposed for biogas production via food and yard waste processing as an additional renewable energy source.

3.2.3. Scenario analysis with technology hubs integration

In this study, the conceptual linkages of technology integration include solar panel, wind turbine, aboveground water retention and storage system (i.e., wet retention pond), green roof in hospital building, small anaerobic digestion system, food and yard waste collection with the potential integration to building energy consumption (**Figure 9**). The proposed technology hub integrations in a FEWW nexus are listed in **Table 10** via different scenarios. Each of the technology integration is related to a retrofit alternative where the original building design is designated as A0.

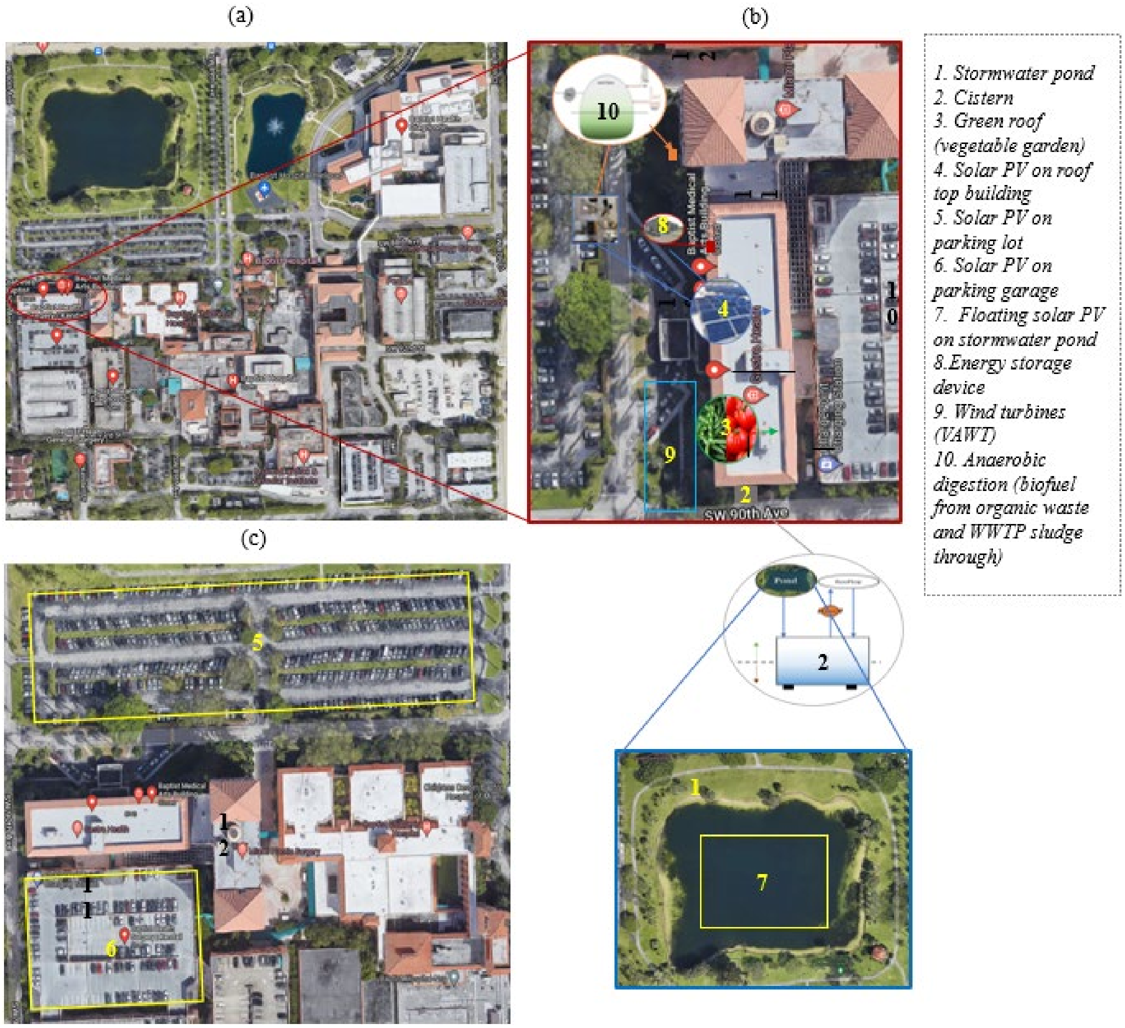


Figure 9. (a) Site map for community-scale FEWW system in Baptist Hospital Miami, USA, (b) conceptual diagram of technology hub integration into the case Medical Arts Building and (c) location of solar energy technologies in the community (Accessed Feb 2022 from Google Maps)

Table 10. Renewable energy technology integration for FEWW-building system analysis

Study retrofit alternative	***A0***	***A1***	***A2***	***A3***	***A4***	***A5***	***A6***
Food							
Green roof (vegetable garden)		✓	✓	✓	✓	✓	✓
Energy							
Rooftop solar PV system		✓	✓	✓		✓	✓
Parking lot and parking garage solar PV systems			✓	✓		✓	✓
Floating solar PV system				✓		✓	✓
Wind (VAWT) System					✓	✓	✓
Anaerobic Digestion							✓
Energy storage system		✓	✓	✓	✓	✓	✓
Water							
Stormwater pod (retention system)		✓	✓	✓	✓	✓	✓
Waste							
Anaerobic digestion							✓

3.3. Methodology

The analytical framework adopted is portrayed in **Figure 10**. In this study, seven steps of the integrated assessment were considered for evaluating the community-scale FEWW system with technology hub integration via a nexus approach as follows.

Step 1: Selection of study site and representative building (**Figure 9**), Step 2: The potential technologies for integration related to a FEWW nexus were identified (**Figure 9**, and **Table 10**).

Step 3: The community-scale retrofit technologies were integrated with different alternative scenarios (based on **Table 10**), and energy consumption/demand were assessed using EnergyPlus V9.1.

Step 4: Simulation of the distributed production and storage of materials and energy flows into, out of, and within a selected community given their consumption patterns and supply chains associated with various alternatives/scenarios using Stella program.

Step 5: Building energy supply and demand (e.g., energy balance) was re-valuated using the EnergyPlus version 9.1 software with and without the adaptation strategies and modify technology hub integration (based on Step 3).

Step 6: The analysis of the whole system for the case-based retrofit program was extended to community scale for evaluating the community sustainability and/or resilience with the adoption of identified technology hubs based on a set of sustainability indicators.

Step 7: A life cycle assessment (LCA) was conducted to evaluate the GHG emissions associated with different alternatives and carbon/water footprint for different technology hubs integration toward sorting the decarbonization pathways for decision-making.

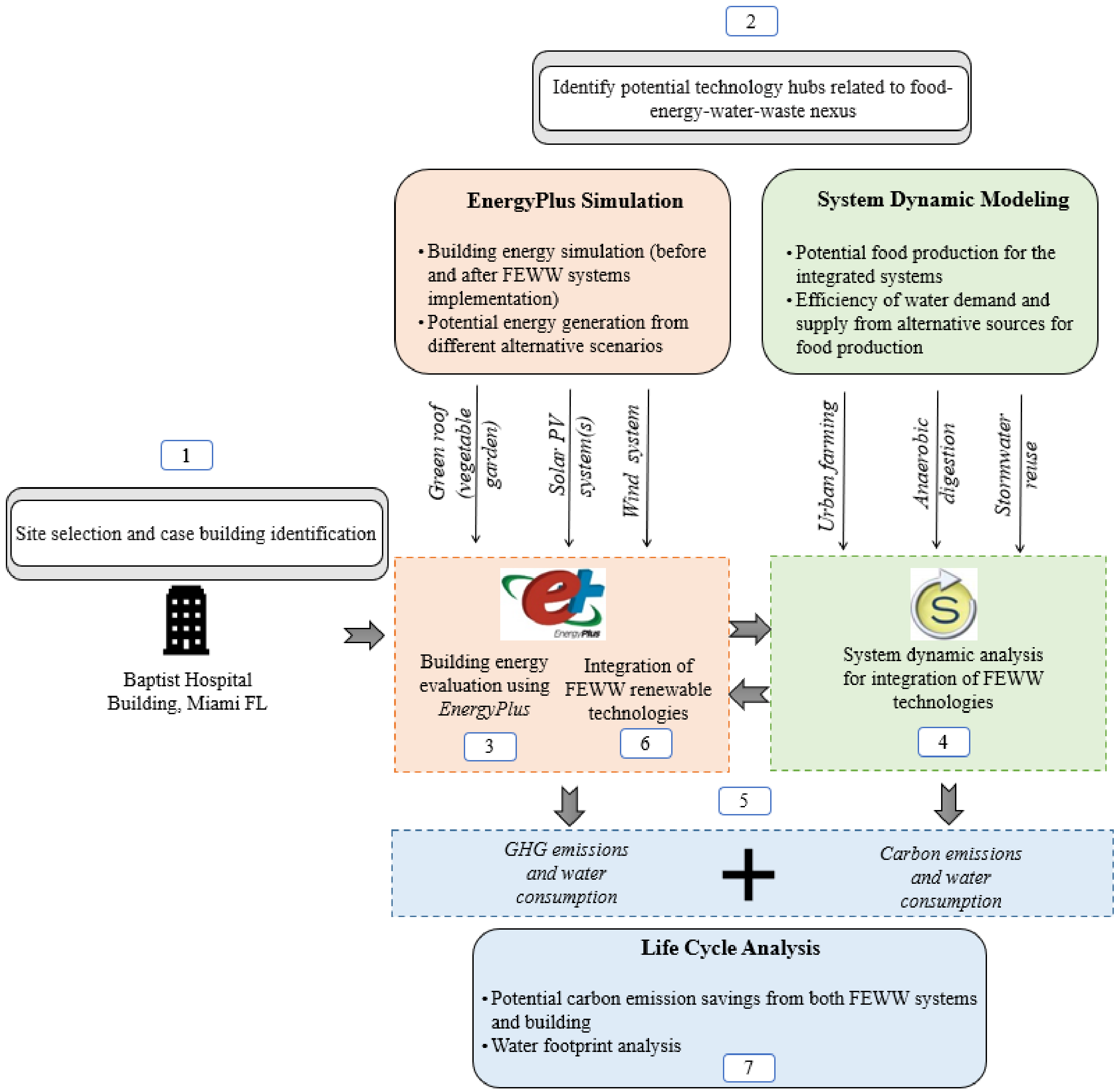


Figure 10. Analytical framework with the synergies between energy simulation tool, LCA, and SDM for integrated assessment in a FEWW nexus.

3.3.1. Building energy analysis simulation for integrating FEWW nexus using EnergyPlus

EnergyPlus simulation program is an integrated simulation environment, which can simulate loads and systems simultaneously, accurate air conditioning and electrical systems in whole building[157, 158]. This has been extensively used in simulating building energy performance globally. For example, Kamal et al.[159] evaluated the control strategies of thermal energy storage and optimal operational energy uses in the commercial building in Tampa, Florida (USA). Pisello et al.[147, 160] studied the energy performance for cool roof system, and human behavior[161] using EnergyPlus in Perugia, Italy. Similar studies can be found in Chicago (USA)[162], in Berlin (Germany)[145], in Baltimore and Phoenix (USA)[80], in Cyprus[149], and in Turkey[132]. In order to assess the effect of implementing the proposed FEWW nexus at the community-scale, the dynamic simulation model was adopted with EnergyPlus V9.2 simulation environment[157]. The dynamic simulation modeling consisted of a few steps. In the first step, the model of the current building scenario was elaborated. Secondly, a new scenario was developed with varying the proposed scenarios to evaluate the effect of varying roof-top technologies, i.e., the existing roof system and the green roof system with solar PV system(s), wind energy and anaerobic digestion (**Figure 9** and **Table 10**). The weather date specific to the study region was obtained directly from EnergyPlus database based on the measurements at the Miami international airport weather station. The input details for modeling the green roof in EnergyPlus known as EcoRoof is summarized in **Table A1**.

3.3.2. Integration of Renewable Energy Technologies

The solar and wind energy simulations corresponding to the building retrofit alternatives were also modeled using EnergyPlus program. EnergyPlus employs the PVWatts calculator from United States National Renewable Energy Laboratory[163], for solar (PV) generation specific to a geographical region and the wind turbine model for VAWT energy generation[164]. The summary of the wind turbine generator inputs is described in **Table A2**; greater details in the EnergyPlus setting for simulation can be found out in the Supplementary Information in Valencia et al.[82]. Lastly, the analysis of a small-scale anaerobic digester is modeled using the U.S. EPA Co-digestion Economic Analysis Tool (Co-EAT). Although its primary use is for economic analysis for decision-making of food waste co-digestion at a wastewater treatment plant or farm digester, some of its outputs include biogas production[165]. A summary of the input/output parameters for the Co-EAT tool is listed in **Table A3**. Additionally, for energy storage energy system, the battery energy storage systems are considered based on its performance and integration with renewable energy technologies[130]. This study considers energy storage system for the purpose of possible storage of excess renewable energy.

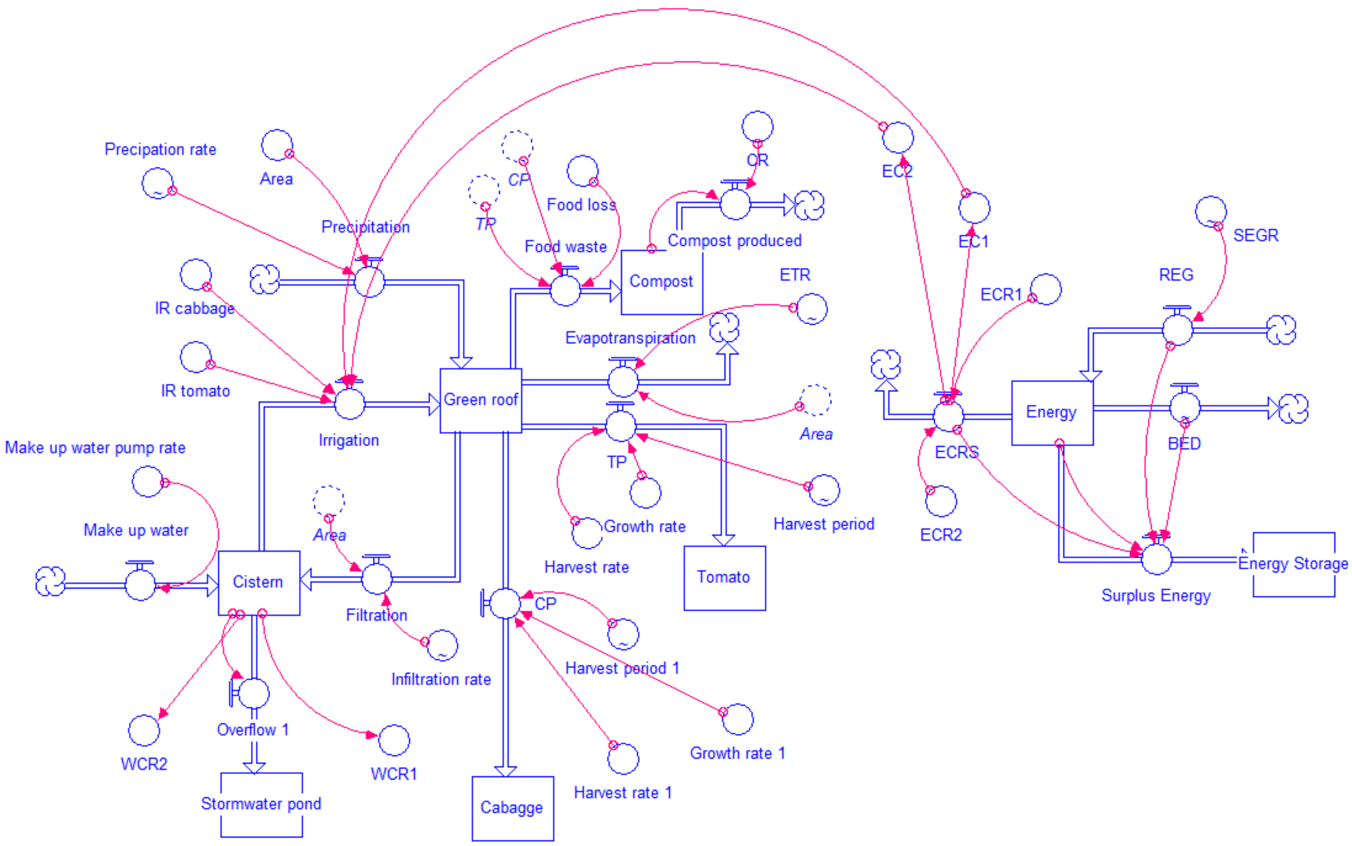
3.3.3. Necessary and Sufficient Conditions in the Proposed FEWW Nexus

The proposed retrofit alternatives in the FEWW nexus should satisfy the necessary (interconnection) and sufficient condition (interdependence) among the food, energy, water, and waste components. The interdependencies and interconnections for each retrofit alternative are summarized for the proposed FEWW nexus in **Figure 11**. These necessary conditions can be confirmed around the six sub-diagrams to support different sustainability patterns. Here the interconnection in this nexus approach is formed in the food-water (stormwater reuse for green roof crop irrigation), water-food (reduction in virtual water), energy-food (renewable energy for crop irrigation system), energy-water (energy to pump water for irrigation), and food-energy (biofuel from yard waste) relationships. For food-water nexus, one of the benefits of producing local crops from the green roof vegetable garden with stormwater reuse is the reduction of virtual water embedded in the imported vegetable, if not produced locally. Overall, these relationships focused on the building energy performance are aimed at reducing $CO_{2\text{-eq}}$ emissions and increasing renewable energy generation to offset building energy demand from utility grid toward decarbonization.

3.3.3.1. System Dynamic Modeling Using Stella

Several types of systems analyses were developed for a FEW nexus, including index-based approach[166], input-output modeling including multi-regional input-output[167, 168], mathematical modeling[169], LCA[170, 171], network modeling[172], agent-based modeling[173], survey with factor analysis[174], optimization models[175, 176], system dynamic modeling (SDM)[21, 177], and system dynamic model with fuzzy cognitive mapping[178]. In addition, Susnik[179] analyzed the FEW-GDP system globally and found that GDP is more deeply correlated to electricity consumption and water withdrawals than food production. Wicaksono and Kang[180] proposed simulation model in a FEW nexus based on a system dynamics concept to assess relevant resources for implementing national energy policy changes in South Korea. The model considered the feedback from water, energy, and food sectors with equal weight, and was also capable of identifying the influential factors affecting resource availability through feedstock analysis (e.g., interconnection of resources). In the current study, the dynamic relationships of energy generation and consumption, stormwater management and utilization, and food production were evaluated collectively based on a SDM approach using Stella software (**Figure 12**). With emerging dynamic network establishments and simulation structures, SDM was tied to LCA for assessing the carbon emissions and analyzing potential synergies and possible trade-offs among different alternatives toward decarbonization in the case study.

Figure 11. Conceptual diagram demonstrating the interdependencies and interconnections in the FEWW nexus for each retrofit alternative.



IR: Irrigation rate; TP : Tomato Production green roof system; CP: Cabbage production green roof system; CR: Compost rate; ETR: Evapotranspiration rate; WCR 1: Water consumption rate TP; WCR 2: Water consumption rate CP; EC 1: Energy consumption TP; EC 2: Energy consumption CP; ECRS: Energy consumption rate sum; ECR 1: Energy consumption rate TP; ECR 2: Energy consumption rate CP; REGS: Renewable energy generation rate; sum; generation rate; BED: Building energy demand

Figure 12. Dynamic modeling of food, energy, water management and waste with the proposed FEWW nexus system (holistic representation of A1-A6)

For scenario A1-A6, the water and energy requirements for the selected vegetables (tomato and cabbage) production and the production per unit area were based on relevant literature (shown in **Table A4**). All of these values were important input parameters for the proposed SDM. The potential energy demand corresponding to crop irrigation can be estimated using Eq. (7).

$$EC_{green\,roof} = \sum_{t=12} \frac{YPA_{crop,i} \times ECR_{crop,i} \times A_{cultivation,i}}{conversion\left(12\frac{months}{y}\right)} \qquad (7)$$

where $EC_{green\ roof}$ is the monthly energy consumption in the case of green roof irrigation (kWh), $YPA_{crop,i}$ is the annual crop yield per area (kg/m^2.y) for vegetable i, $ECR_{crop,i}$ is the energy consumption rate per unit production of vegetable i (kWh/ kg), $A_{cultivation}$ is the area corresponding to each crop cultivated (m^2).

The monthly water consumption (mainly for irrigation) for the crop production (C_{crop}) can be estimated by the following Equation (Eq. (8)).

$$WC_{green\ roof} = \sum_{t=12} \frac{YPA_{crop,i} \times WD_{crop,i} \times A_{cultivation,i}}{conversion\left(12\frac{months}{y}\right)} \tag{8}$$

where $WC_{green\ roof}$ is the monthly water consumption rate (L), $WD_{crop,i}$ is the water depletion (irrigation needed) (L•kg^{-1}) for each vegetable i, .In the proposed FEWW system, the potential food (e.g., selected vegetable) crop production ($C_{production}$) can be estimated by using Eq. (9).

$$C_{production} = \sum_{i=2} [YPA_{crop,i} \times A_{cultivation}] \tag{9}$$

3.3.3.2. Water system analysis integrating green roof and stormwater

A green roof with a cistern for stormwater reuse offers a sustainable solution that utilizes unused space to treat and store stormwater runoff. This system is normally comprised of a green roof with its drainage system connected to a cistern. The cistern in turn supplies irrigation water to the roof via a pump. A supplemental water source from a stormwater wet detention pond is also connected to the cistern to provide water should there is not sufficient water for irrigation. The pump can be either electric or solar powered water pump depending on the rooftop conditions and project goals. The irrigation is managed via a controller, similar to what is widely used for home lawn/green roof irrigation, which only irrigates on the prescribed times unless sufficient rain has fallen within 24 hours of the intended irrigation event. Recycling the stormwater runoff and irrigating the green roof with stored water enhances the water availability affecting some hydrologic factors such as evapotranspiration, the filtering in the growth media, and water holding capabilities of the plants and growth media. It leads to greatly reduce the volume of stormwater runoff leaving the green roof site.

In order to achieve this goal, a cistern needs to be used to store the water between irrigation events. In the water balance analysis, the only two ways water will leave the green roof include evapotranspiration (ET) and stormwater runoff (F) when the growth media mixes reach their storage capacity in large storm events. The only two ways water will enter the system is from precipitation (P) and from a supplemental source that is of a quality that is acceptable for irrigation use (I). The efficiency of the system is determined from the total precipitation and the total overflow from the cistern. Some studies showed that ET is not dependent on growth media depth but rather local meteorological conditions (e.g., air temperature) where dry metrological conditions cause higher ET rates[181, 182]. The Blaney-Criddle equation is presented and analyzed to determine its acceptability for ET determination and make the model relevant for cistern design in all geographic regions (Eqs. (10)-(12)). In this analysis, the green roof system that consists of a thermoplastic membrane with a geosynthetic protection layer above it, a 50.8 mm (2 inches) gravel drainage layer above that, a non-woven separation fabric above that, a 152.4 mm (6 inches) layer of growth media with vegetation on the top. In addition, a cistern with a volume equivalent to 20 m^3 is also part of the design. Stella can help formulate a system dynamic model to address the dynamics of water balance of a green building with a green roof, a cistern and a wet detention pond, an expression for the filtrate factor as it varies with soil conditions, precipitation, evapotranspiration, and irrigation amount that can be derived (Eq. (10)).

$$\frac{dMs}{dt} = P + I - ET - F \tag{10}$$

Making the assumption of a finite difference the following simplification can be made:

$$\frac{\Delta Ms}{\Delta t} = P + I - ET - F \tag{11}$$

This equation is in terms of volume per unit time and needs to be multiplied through by the time step to get volume. This equation then simplifies as follows:

$$\Delta Ms = P + I - ET - F \tag{12}$$

The precipitation, ET, infiltration solar electricity generation inputs used for SDM are summarized in **Table 11**.

Table 11. Water data for system dynamic modeling in the Baptist Hospital.

Month	Precipitation* rate cm (inch)	Evapotranspiration rate⸸ cm (inch)	Infiltration* rate cm (inch)	Solar electricity generation ($kWh^{\bullet}m^{-2}$)$^{\Delta}$
January	1.27 (0.5)	0.02 (0.008)	1.25 (0.49)	154
February	7.37(2.9)	0.03 (0.013)	7.33 (2.89)	162
March	4.75 (1.87)	0.04 (0.016)	4.71 (1.85)	197
April	7.14 (2.81)	0.05 (0.021)	7.08 (2.79)	199
May	6.81 (2.68)	0.06 (0.024)	6.75 (2.66)	198
June	31.60 (12.44)	0.05 (0.020)	31.55 (12.42)	175
July	20.78 (8.18)	0.06 (0.023)	20.72 (8.16)	184
August	18.52 (7.29)	0.05 (0.020)	18.47 (7.27)	188
September	30.78 (12.12)	0.05 (0.021)	30.73 (12.10)	160
October	12.47 (4.91)	0.04 (0.016)	12.43 (4.89)	171
November	11.13 (4.38)	0.03 (0.011)	11.10 (4.37)	150
December	3.02 (1.19)	0.02 (0.007)	3.00 (1.18)	147

* Data from 2021 ⸸ Data from 2019 $^{\Delta}$ PVWatts Calculator (Miami, FL)

3.3.3.3. Carbon and water footprint assessment

Based on the proposed retrofit alternatives, carbon and water footprints were calculated in terms of GHG emissions (as CO2 eq) in comparison to the baseline of existing building energy consumption from the utility grid. The GHG emissions pertaining to electricity consumption in the buildings can be determined via EnergyPlus based on the building energy demand in which the carbon emission factor per electricity generated based on utility grid can be adapted from the EPA eGrid data set[183], following Eq.(13).

$$GHG_{building} = CEF_{grid} \times E_{demand} \quad (13)$$

where $GHG_{building}$ is the quantity of GHG emissions (kg $CO_{2\text{-eq}}$) of building energy demand from a utility grid, CEF_{grid} is the carbon emission factor per electricity generated based on utility grid (kg $CO_{2\text{-eq}}$•kWh-1), and E_{demand} is total electricity consumption of buildings (kWh).

The reduction of GHG emissions (as $CO_{2\ eq}$) is calculated by Eq.(14) to account for the offset by renewable energy technologies.

$$GHG_{FEWW\ tech.} = \sum_{j=3}\left[CEF_{ren\ tech,} \times E_{production,j}\right] \quad (14)$$

where $GHG_{FEWW\ tech.}$ is the amount GHG emission offset (kg $CO_{2\text{-eq}}$) via energy generation from technologies j (e.g., solar PV, wind), $CEF_{ren,\ tech.}$ is the carbon emission factor per electricity generated for the renewable energy technologies (kg $CO_{2\text{-eq}}$•kWh^{-1}), and $E_{production,\ j}$ is the total amount of renewable energy generated (kWh).

$$GHG_{crop\ production} = \sum_{i=2}\left[CEF_{ren\ tech\ ,j} \times E_{crop,i}\right] \quad (15)$$

where the $GHG_{crop\ production}$ is the annual amount GHG emission offset (kg $CO_{2\text{-eq}}$) for the production of crop i in a period of one year, $CEF_{ren.\ tech,\ i}$ is the carbon emission factor per electricity consumed obtained from renewable energy in cultivation of vegetable i (kg $CO_{2\text{-eq}}$/ kWh), and E_{crop} is the total amount of energy demand from crop irrigation.

Thus in Eq. (16), GHG_k *is* the net annual GHG emission (kg $CO_{2\text{-eq}}$) for alternative *k,* accounting for carbon emission reduction in relation to building consumption. The GHG emission factors associated with $CO_{2\text{-eq}}$ pertaining to renewable and nonrenewable energy sources are described in **Table A5**.

$$GHG_k = \sum_{i,i} GHG_{building} - (GHG_{crop\ production,i} + GHG_{FEWW\ tech.,j}) \quad (16)$$

The water footprint associated with water consumption savings follows similar equations for its calculation. WC_{building} is the water consumption (L) related to electricity consumption of building in kWh and water consumption per energy generation (WCF_{grid}) in L•kWh^{-1}.

$$WC_{building} = WCF_{grid} \times E_{demand} \quad (17)$$

The annual water footprint (L) for the production of crop *i* is determined by Eq. (18), utilizing the factor per electricity generated for the renewable energy technologies and irrigation energy demand.

$$WC_{crop\,production} = \sum_{i=2}\left[WCF_{ren\,tech\,,j} \times E_{crop,i}\right] \quad (18)$$

where $WC_{crop\ porduction}$ is the amount of water (L), $WCF_{ren\,tech\,,j}$ is the factor per electricity generated for the renewable energy technologies (L•kWh^{-1}). $E_{crop,i}$ is the irrigation energy demand (kWh). Following Eq. (19), water footprint for crop growth is estimated.

$$WC_{FEWW\,tech.} = \sum_{j=3}\left[WCF_{ren\,tech,i} \times E_{production}\right] \quad (19)$$

where the $WC_{FEWW\ tech.}$ is the amount water footprint (L) of energy generation from technologies *j* (solar PV or wind) that can be saved to replace the demand from a utility grid, $WCF_{ren,\ tech.,i}$ is the water consumption factor per electricity generated for the renewable energy technologies (L•kWh^{-1}), and $E_{production}$ is the renewable energy generated (kWh). The net annual water footprint is thus determined from Eq. (20). The water consumption factors associated with renewable and nonrenewable energy sources are described in **Table A6**.

$$WC_k = \sum_{i,i} WC_{building} - (WC_{crop\,production,i} + WC_{FEWW\,tech.,j}) \quad (20)$$

where WC_k is the net annual water footprint (L) for alternative k. The carbon and water emission factors associated with renewable energy generation (solar PV and VAWT) were obtained from the previous LCA literature as described in the previous section.

3.4. Results and Discussion

3.4.1. Energy and Water Performance of Building for The Proposed FEWW System

EnergyPlus provides monthly energy demand pertaining to the energy consumed by the building. With the aid of EnergyPlus, the annual net source energy demand for all building energy use was determined as 3.376×10^6 GJ accounting for transmission, production, and delivery losses(184) (A0). This value is larger than the counterpart in A1 which is 3.368×10^6 GJ for buildings with green roof accounting for an energy reduction of 0.23% driven by heat and cooling effects. The results pertaining to energy reduction from green roof implementation of this coastal city is comparable with the previous analysis performed in a similar framework(82). With the inclusion of the rooftop solar PV system along with green roof (A1), the solar energy generation was 411.59 GJ. In this alternative A1, the energy provided by the solar PV was 1.22% of the total energy demand. For A2, the expansion of the solar PV systems (i.e., rooftop, parking lot and parking garage) results in the solar energy generation of 1.51×10^4 GJ. However, in A3, the inclusion of a floating solar PV system as an integral part of the existing solar PV system results in the solar energy generation of 2.44×10^4 GJ. The energy demand sustained by the solar PV system was determined as 45% and 72%, for A2 and A3, respectively. On the other hand, the net source energy demand was determined as 6.15×10^4 GJ for the integration of VAWT and green roof (A4) with a wind power electric load of 1.86×10^3 GJ, and wind turbine electricity generation was 930 GJ, accounting for 1.51% of net source energy demand. It is noticeable that the building energy demand remains as 3.368×10^6 GJ for A1, A2, and A3. The net source energy demand is also sustained as 6.15×10^4 GJ when combing all the selected solar and wind energy technologies with the green roof (A5); meanwhile, the total renewable energy generation was increased to 2.53×10^4 GJ, sustaining about 41 % of net source energy demand. Nevertheless, the inclusion of anaerobic digestion in A6 does not contribute significantly to the total energy generation given that the energy generation of 0.291 GJ from anaerobic digestion is only a small fraction of 2.53×10^4 GJ. Yet, like solar and wind energy production, the biogas production can vary daily. It is known that small-scale anaerobic digestion is also referred as micro-scale digestion that produce between 5-15 kW employed in small comminutes (e.g., households)(185).

These values generated by EnergyPlus were used as inputs in the SDM corresponding to the building energy demand. **Table 12** summarizes a set of predictions for different retrofit alternatives, including the potential annual energy generation (P*)* in kWh, building energy consumption (R) in kWh, FEWW system energy consumption (Q) without including the building in kWh, and potential energy savings from a FEWW system (S where S= [P-(Q+R)]). This table helps specify all energy inputs/outputs from/to grid of the building reflecting the impact from a FEWW system (I/O), based on the comparison between building energy consumption and renewable energy generation (C) (i.e., C = [[(R-S)*100]/R]). If C is > 100 then renewable energy in the FEWW system is not enough for sustaining energy demand and if S is negative then energy (I/O) comes from the grid, but if S is positive then surplus energy can be transferred to grid from the energy storage system.

Table 12. Potential annual energy generation, energy demand and energy storage for different scenarios in this FEWW nexus

Alternatives	Potential energy generation from renewable energy* (kWh/year) (P)	Energy consumption of building (kWh/year)[#] (R)	Energy consumption for FEWW system (food production) (kWh/year) (Q)	Potential energy savings from FEWW system (kWh/year) (S)	Comparative energy analysis for building vs. FEWW system (%) (C)	Energy input/output from/to grid energy (I/O)
A0	--	2.81×10^6	--	--	--	Grid
A1	1.14×10^5	2.80×10^6	4.76×10^3	-2.69×10^6	196.1	Grid
A2	4.09×10^6	2.80×10^6	4.76×10^3	1.28×10^6	-54.4	Energy Storage
A3	6.77×10^6	2.80×10^6	4.76×10^3	3.96×10^6	-41.4	Energy Storage
A4	2.58×10^5	2.80×10^6	4.76×10^3	-2.55×10^6	191.0	Grid
A5	7.03×10^6	2.80×10^6	4.76×10^3	4.22×10^6	-50.5	Energy Storage
A6	7.03×10^6	2.80×10^6	4.76×10^3	4.22×10^6	-50.6	Energy Storage

* Renewable energy refers to solar PV, VAWT energy and/or small-scale anaerobic digestion [#]Values correspond to site energy

Overall, there is an increase in potential energy generation from renewable according to the technical settings in A1-A6 due to the inclusion of additional renewable energy technologies except for A4 that corresponds to the implementation of wind energy only. There is not much difference in energy generation potential between A5 and A6 suggesting the small impact that the anaerobic digester had in the energy generation portfolio. Further comparison can be conducted with as a percentage between the building energy demand and potential energy saving from the FEWW system. A1 and A4 do not generate sufficient renewable energy to sustain the FEWW system and meet the building's demand as they can only meet 4% and 9% of the total energy requirements, thereby requiring the same grid energy almost. But alternatives A2, A3, A5, and A6 can sell excess renewable energy back to the utility grid via energy storage devices, as they can generate about 146%, 241%, 251% and 251%, respectively, relative to the total energy demand by the entire FEWW system. The alternatives A6 and A5 showed the highest renewable energy harvesting potential equivalently, followed by A3 and A2. This observation is evidenced by the negative S where negative values represent required energy derived from the utility grid, and positive value indicates surplus energy from the renewable energy harvesting. When comparing the energy demand to sustain food production (i.e., irrigation) of 4.76×10^3 kwh annually and the energy generation from renewable energy, the percent of this renewable energy generation designated to food production is 4%, 0.1%, 0.07%, 1.8%, and 0.07% for A1, A2, A3, A4, as well as both A5 and A6, respectively. It reflects an increase in available renewable energy for meeting building energy demand as the urban farming technologies can be implemented. Further, the reduction from GHG emissions accounting for the carbon emissions offset by the generation of renewable energy were 4.3% for A1, 149% for A2, 241.2 % for A3, 9% for A4, as well as 250%

for both A5 and A6. Findings indicated that both A5 and A6 have the lowest ones followed closely by A3 (**Table 13**).

The annual water consumption pertaining to water demand for building energy remained the same as 2.12 ×107 L (**Table 13**) even with the slight reduction of the building energy consumption attributed to the green roof. However, in comparison to A0, the highest water consumption savings of approximately 251% was achieved by both A5 and A6. But A4 had the lowest water savings of 4%. The results support the reduction of water consumption for the alternatives with solar PV systems and A3, and A5 and A6 exhibited the greatest water reduction potential. Lastly, for the food production in the FEWW system, the annual crop yield was 2.03 metric ton (tonne), and 0.05 metric ton (tonne), for tomato and cabbage, respectively. The estimated makeup water which represents the quantity of stormwater needed to meet irrigation demand remained constant as 2.40×105 L•month^{-1}. This is based on the dynamic observations in the monthly precipitation with fluctuations (Fig. 1A) where it is expected for precipitation to be the primary contributor in a conventional agriculture system without any form of irrigation.

Table 13. CO_{2-eq} emission, potential food production, and water requirements for different scenarios in this FEWW nexus with respect to energy demand/generation

Alternatives	Annual grid electricity CO_2 emission (kg eq)*	Annual renewable energy CO_2 emission offset (kg eq)*	Net CO_2 emission for building and FEWW system (kg eq)ⱡ	Saving compared to A0 (%)	Annual building energy water consumption (L)	Annual renewable energy water consumption offset* (L)	Net water consumption for building and FEWW system (L)ǂ
A0	1.31×10^6	--	1.31×10^6	--	2.12×10^7	--	2.12×10^7
A1	1.31×10^6	5.36×10^4	1.26×10^6	4	2.12×10^7	8.64×10^5	2.03×10^7
A2	1.31×10^6	1.95×10^6	-6.44×10^5	149	2.12×10^7	3.16×10^7	-1.04×10^7
A3	1.31×10^6	3.16×10^6	-1.85×10^6	241	2.12×10^7	5.12×10^7	-3.00×10^7
A4	1.31×10^6	1.21×10^5	1.19×10^6	9	2.12×10^7	1.95×10^6	1.92×10^7
A5	1.31×10^6	3.28×10^6	-1.97×10^6	251	2.12×10^7	5.32×10^7	-3.20×10^7
A6	1.31×10^6	3.28×10^6	-1.97×10^6	251	2.12×10^7	5.32×10^7	-3.20×10^7

* Obtained from EnergyPlus ⱡ Eq.9 ǂ Eq. 12.

3.4.2. Sustainable Pathways for Decarbonization In An FEWW Nexus

In congruence, decarbonization is a complex endeavor, specifically with respect to decarbonization in the power supply sector. As such, to accommodate for these challenges, policy makers need to understand the appropriate decarbonization pathways[186]. Hence a decarbonization pathway analysis can be explored by considering the carbon emissions related to retrofit alternatives. It was assumed that the implementation of a FEWW nexus will be in progress in the next 10 years and the potential reduction in GHG emissions can be expected when considering the renewable energy generation to replace energy from utility grid (**Figure 13**). For instance, A4 has the third highest net annual carbon footprint due to energy consumption (after A1 and A0); however, it should be noted that for this retrofit strategy, the wind energy system produced the least amount of energy relative to all the alternatives. Yet, when implementing solar energy as in the case of A5 and A6, it can produce the lowest annual net carbon emissions for the FEWW system with buildings. As such, alternatives A3, A5, and A6 have the smallest annual net carbon footprint with the largest renewable energy generation potential among the retrofit alternatives in comparison to A0. If the implementation of the building retrofit strategies is assumed to be in place within the next 10 years, the preferred retrofit strategies based on the annual potential of carbon footprint reduction follow the order of A5 or A6, then A3 and A2 in sequence.

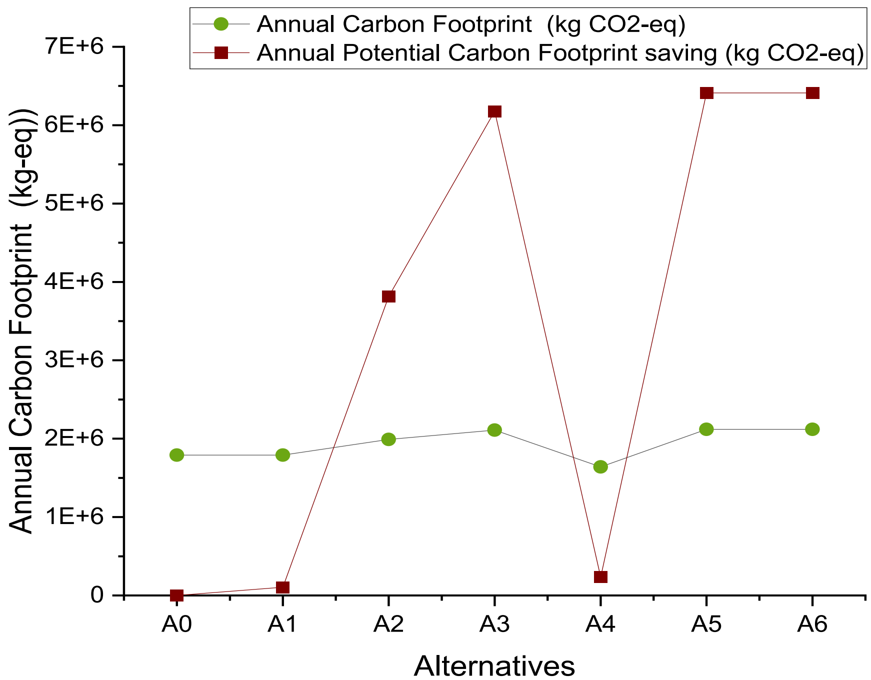


Figure 13. Decarbonization Pathway for retrofit alternatives in FEWW nexus (in terms of kg CO_2-eq•kWh^{-1}) comparing carbon footprint and potential carbon footprint savings

3.6. Final Remarks

Transitioning to a low carbon community set forth by many global agencies have urged the need to explore existing building retrofit strategies in urban areas. This study assessed building energy retrofit strategies and decarbonization pathways in a community-scale FEWW Nexus. The results show that the implementation of a green roof and a solar energy system can save total utility-grid energy demand by 0.23 % and 1.22%, respectively, in A1. The alternatives with highest renewable energy generation are A5 or A6 where the energy demand sustained by the renewable energy technologies ranged from 41-72% leading to reduce the energy demand from utility grid. The lowest annual net carbon footprint can be achieved by A6, A5, and A3 in the community-scale

FEWW system including buildings. While the water footprint did not have large variation among these alternatives, the difference was observed in A6, A5, and A3 with the lowest water consumption in the community-scale FEWW system including buildings. Alternative A4 had one of the highest net annual carbon footprints while the wind energy system produced the least amount of energy among other alternatives. Overall, A3, A5, and A6 also had the smallest carbon footprint and largest renewable energy generation potential groupwise. As such, a retrofit strategy can be implemented by slowly increasing the implementation of renewable energy technologies and progressing from A2 to A3 to A5 and/or A6 in a FEWW system. Lastly, given that the retrofit alternatives explored in this study were primarily focused on solar PV systems, future building energy analysis can include the evaluation of the new technology of PV windows for a potential replacement of conventional windows in buildings.

CHAPTER 4: SUSTAINABILITY TRANSITIONS OF URBAN FOOD-ENERGY-WATER-WASTE INFRASTRUCTURE: A LIVING LABORATIRY APPROACH FOR CIRCULAR ECONOMY[2]

4.1. Introduction

Population growth and migration, economic development, and climate change continuously reshape the evolutionary pathway of many urban infrastructure systems. Globalization and urbanization not only create environmental impacts but also increase resource demand for sustainment and growth. These activities result in various environmental impacts, including the increase in greenhouse gas (GHG) emissions(187), exacerbation of the urban heat island effect(188), ecosystem degradation(189), waste disposal(190), water pollution(191), nonpoint source pollution via stormwater runoff(192), and land-use and resources competition(193). Facing such global change impact, it is vital to understand the interdependencies and interconnections among the four sectors (food, energy, water, and waste) in a nexus framework and to optimally manage water, food, and energy resources, and mitigate their (negative) impact on the environment. This is more critical since the initial analysis of a typical food, energy, water (FEW) nexus may not be sufficient to incorporate all the elements represented in their interconnections, which tend to exclude waste. These traditional interrelationships in food, energy, and water sectors missed the emphasis of waste streams, as it is impractical to produce, distribute, and consume food, energy, and water without waste generation(23). A system dynamics model (SDM) can portray material and energy flows

[2] Authors: Valencia, A., Zhang, W., & Chang, N. B. (2022). Sustainability transitions of urban food-energy-water-waste infrastructure: A living laboratory approach for circular economy. *Resources, Conservation and Recycling*, *177*, 105991.

across the FEW nexus. Thompson et al.[194] used various modeling approaches such as agent-based modeling and climate dynamics in an urban FEW nexus, emphasizing food production to explore sustainability and resilience. Hussien et al.[21] conducted a SDM for the demand assessment of FEW and the generation of wastewater and organic waste at household scale. The FEW nexus approach has been expanded to include other sectors and variables to address sustainability; for instance, the Food-Waste-Water-CO2 nexus has also been explored to study the impacts of urban sustainability[195]. Recently, an ecosystem service with optimization was evaluated for a FEWW nexus applied to the New York State bioenergy production by Garcia et al.[25]; additionally, Zhao and You [196] explored the use of a FEWW nexus for New York State during the COVID-19 pandemic to address increased waste generation, which was coupled with energy generation. Yet, little research has thoroughly evaluated food, energy, water, and waste (FEWW) nexus via SDM to account for urban sustainability transitions under climate change impact. It is thus essential to consider and explore the complex feedback systems in integrating the four sectors of an urban FEWW nexus in this study.

The interlinkages between the FEWW sectors are numerous, with multiple layers of dependencies and interconnections associated with the available resources and their external climatic, geopolitical, and socioeconomic drivers. These entities can affect a nexus, as policymakers and stakeholders play an essential role in developing various urban FEWW nexuses via various public-private partnerships that coexist multiple layers of interactions and behaviors of distinct entities[197]. However, there is a disconnection between the governance structure and function affecting these sectors due to the uncoordinated nature of policies among the sectors[198]. As such, the proposed nexus analysis in this study involves managing the interrelations and tradeoffs in the four sectors through the implementation of policy instruments and the analysis of cost-benefit-risk tradeoffs. Hence, a risk-based transformation of critical urban infrastructure systems regarding food security, energy resilience, water sustainability, and cleaner production under global change impact requires either bottom-up or top-down decision-making processes, or even both (i.e., a hybrid mode).

If a metropolitan region is considered a living organism, then the overall mass and energy flow with intensive interactions in a FEWW nexus can be described by urban metabolism and employed to evaluate the metropolitan development of a city and suburban/rural environment. This viewpoint can advance our understanding of the social, physical, and environmental factors that influence the adaptive transformations of critical urban infrastructures at a regional scale. Thus, bottom-up or top-down decision-making processes can be coupled to elucidate the FEWW nexus where the resources flow and resource links related to water, energy, nutrients, and waste materials can be concatenated(199). This nexus expansion can help realize the criticality of system planning for infrastructure transformations via a living laboratory and aggregate resource links and their robustness in response to climatic, economic, environmental, and social changes. The proper integration of multi-agent modeling and multicriteria assessment can help investigate possible evolutionary pathways of urban FEWW infrastructure systems in complex and dynamic environments.

The aim of this study is thus to construct and evaluate an urban FEWW nexus at a regional level by considering sector-based synergies across a suite of planning alternatives associated with operational cost benefit-risk factors under uncertainty. Practical implementation was assessed by analyzing the criticality of the emerging FEWW nexus in Orlando, Florida in the United States (US) to improve the understanding of the adaptive transformation of urban farming supported by both renewable and nonrenewable energy sources and water reclamation/ reuse plans under changing environments (e.g., climate change impacts). In this study, the impacts of the FEWW system and the interactions among the agents/actors can be observed via SDM to support the roles of multiple stakeholders (e.g., government, private, non-profit organizations, and/or state actors) influence on decision making. The four sectors of the FEWW nexus include two water reclamation facilities, one stormwater management agency, one energy generation facility, one municipal landfill, and a set of urban farms to close the loop in a circular economy. Cost-benefit-risk assessment for four planning scenarios via multicriteria decision making was carried out to determine order preference according to the similarity to the ideal solution (TOPSIS). The cost-benefit-risk tradeoff in support of TOPSIS provides a lucid and centralized decision-making process with a risk assessment to prioritize what is important in future infrastructure expansion according to public and private entities. The synergies and interactions among sectors in a FEWW nexus can contribute to sustainable development goals that can address many resource links such as energy from waste, waste for food, water for energy, water for food, etc., in a circular economy. The research questions to be answered include: 1) How does the landfill gas recovery in a FEWW nexus contribute to a circular economy in the Orlando community? 2) Can a well-formulated SDM analysis help policy and decision-makers allocate and prioritize resources using multicriteria decision analysis? 3) What resource limitations are faced in a FEWW nexus in terms of water resilience, food security, and energy sustainability? 4) Will this FEWW infrastructure system respond to the impacts of climate change? 5) Can a FEWW nexus system help decrease the carbon and water footprints?

4.2. Infrastructure System Components in an Urban FEWW Nexus

The area of Downtown Orlando is described by the US Department of Agriculture (USDA) as a food desert, where the community is void of fresh food within an 8 km (5-mile) radius. The USDA defines a food desert as an area characterized by low income and limited transportation, where the population has limited access to supermarkets or grocery stores in accordance with census tracts[200]. Usually, a 1 km^2 area is selected to measure food access, and then the grid size is increased. Low access is determined when at least 33% of the population or 500 people live more than 1.6 km (1 mile) from supermarkets or grocery stores in urban regions. In congruence with limited access to fresh food, West Orlando is also a low-income area. **Figure 14**, obtained from USDA[201], helps visualize the low-income and low access sectors (food deserts) in Orlando, according to 2019 census data and the distribution of the FEW components in the Orlando area. The overall depiction of the low-income, low-access, and food deserts in Orange County is shown by different color scales area-wide (**Figure 14**). The corresponding facility ID, address, and latitude/longitude location are summarized in Supplementary Information Table S1. Further, the light blue color in the map reflects the low-income regions where the family income is less than 80% of the median family income in a metropolitan area or state. In addition, the light pink represents a lack of access to fresh food or market for 33% of the population within a 1.61 km (1 mile) radius. Therefore, all the infrastructure components should be evaluated for integration to facilitate fresh food production, encourage social, economic, and environmental sustainability, and promote urban resilience in a FEWW nexus. The interconnections within a FEWW nexus in the urban area can be further assessed by the concept of urban land teleconnection since it links distant geographical areas with coincident changes in the environment from urbanization[202].

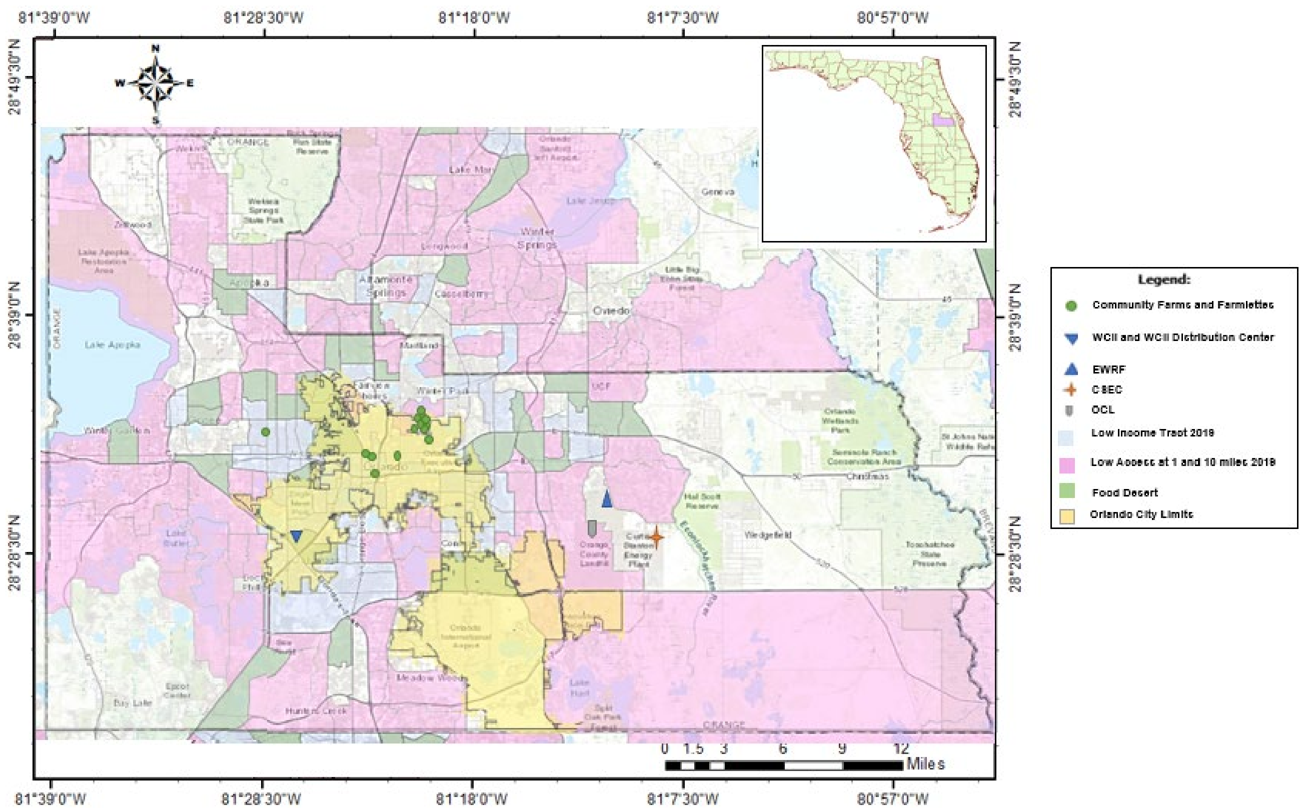


Figure 14. Distribution of low income, low food access, and food desert (USDA[201]) in the Urban FEW nexus components in Orlando, Florida, including the East End Market Urban farm (EEMUF), solar photovoltaic (PV) energy production from the Curtis H. Stanton Energy Center (CSEC), Water Conserv II (WCII), and Eastern Water Reclamation Facility (EWRF) (green color is an overlap of a food desert and low-income areas) and visualization of a low-income food desert in Orlando, Florida (Source: retrieved from USDA according to 2015 data)

The infrastructure system within the FEWW nexus located in Orlando, Florida, encompasses the interrelated material and energy flow between the East End Market Urban Farm (EEMUF), energy production from the Stanton Energy Center (coal, natural gas, landfill gas, and solar photovoltaic (PV) from solar farms), Eastern Water Reclamation Facility (EWRF), Water Conserv II (WCII) Water Reclamation Facility, Water Conserv II Distribution Center (WCIIDC), and Orange County Landfill (OCL). For more detail, refer to Supplementary Information Table S1 for the corresponding facility ID, address, and latitude/longitude locations[203]. As such, the proposed infrastructure system in the FEWW nexus contains interlinkages and interdependencies across the four sectors, including resources links of food-energy, waste-energy, water-food, energy-food, water-energy, and waste-food, where all of the facilities form mutual relationships or partnerships with at least one of the outputs/flows used as the input for another in the system (**Figure 15**). The purpose of formalizing this nexus is to transition the original fragmental interactions to a closed system to take advantage of the possible interdependencies in a circular economy. The four sectors in the FEWW Nexus can be summarized as:

1) Urban Agriculture

The EEMUF, managed by the Fleet Farming organization, consists of a total of 17 farmettes (farm sites) that utilize available front or backyards of homes with an area of around 50–70 m^2, and six community gardens comprising a total approximate area of 2,500 m^2 distributed in Orlando, Florida. According to Fleet Farming ® agriculture program, 5,140 locals were fed with a total produce harvested of 3,497 kg (7,710 lb)[204]. This is a typical top-down approach, using a governance structure with the aid of a centralized farmer market for food supply chain management. The cultivated food is available for the individual owner of the house or the community, as is the case of community gardens. A summary of the possible crops harvested and annual production in the EEMUF is described in Supplementary Information Table S2[203]. Drip irrigation is employed at the farm sites with specified irrigation durations and events during the day. The compost is obtained from Monterey Mushrooms, Inc., situated in Zellwood, Florida, even though composting is performed at some of the farm sites as a supplementary source.

2) Energy Generation

The Curtis H. Stanton Energy Center (CSEC), part of the Orlando Utilities Commission (OUC), supplies energy to the Orlando region. CSEC utilizes coal, natural gas, landfill gas, and solar power for energy production, producing 940 MW from coal, 940 MW from natural gas, 47 MW from Orange County and Holopaw Landfill gas, 6 MW from Solar Farm I, and 13 MW from the Kenneth P. Ksionek Community Solar Farm[205]. In addition, CSEC has a 5.9 MW solar PV array consisting of about 25,000 PV modules[206]. A combustion residual storage area is located in the facility to store fly ash and resultant scrubber sludge.

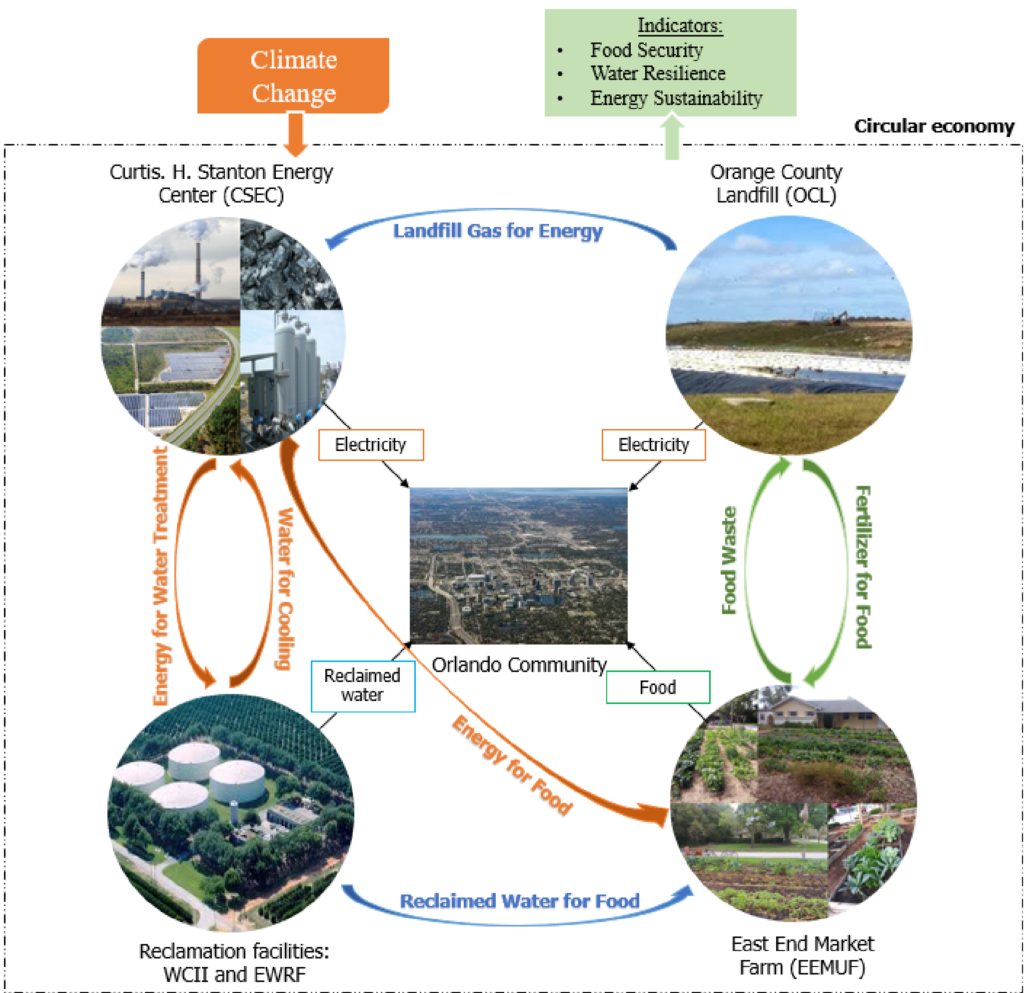


Figure 15. Visualization of interactions and interdependences of each FEWW nexus agent

3) Reclaimed Water Management and Stormwater Reuse

There are two facilities in the FEWW nexus responsible for reclaimed water management. The Water Conserv II (WCII) Water Reclamation Facility has a capacity of $9.46(10)^7$ L•d^{-1} (25 MGD), with a “zero-discharge” goal proposed to utilize the effluent for irrigation and aquifer recharge[(207)]. The biosolids produced from the wastewater treatment process (e.g., sludge) are treated into Class A and land-applied per code B0006. Per 40 CFR Part 203 biosolids rule, both Class A and Class B biosolids can be land applied; however, only Class A is available for distribution and can be comparable to any fertilizer[(208)]. On the other hand, biosolid fertilizer could be banned by several states as well, given the increase in contaminants of emerging concern in wastewater that are challenging to eliminate[(209)] which can prompt more stringent requirement of biosolid minimum pathogen and vector attraction reduction requirements[(208)]. Therefore, biosolid fertilizers were not used for urban farming in this study due to possible secondary contamination. Additionally, WCII supplies treated reclaimed water to the Water Conserv II Distribution Center (WCIIDC) located adjacent to WCII for effluent distribution. The WCIIDC has a permitted flow of $3.06(10)^8$ L•d^{-1} (80.9 MGD) and is responsible for the distribution of reclaimed water for citrus irrigation and 32.37 km^2 (8,000 acres) of rapid infiltration basins (RIBs) and citrus groves. The second reclamation facility is the Eastern Water Reclamation facility (EWRF). The EWRF has a capacity of $9.08(10)^7$ L•d^{-1} (24 MGD), treating municipal wastewater and landfill leachate from the Orange County Landfill. The effluent discharge of reclaimed water consists of wetlands and surface discharge (24% to Little Econlockhatchee river, 67% to wetlands), and 9% for local reuse[(210)]. The biosolids produced in the treatment are landfilled and transferred to a residual management facility (RMF). For stormwater reuse, above-ground storage using wet detention ponds with a total area of 40,000 m^2 is incorporated.

4) Solid Waste Management

The Orange County Landfill (OCL) can receive Class I and Class II material, of which it receives 861,825.5 tonne•y^{-1}. The facility has a two-leachate collection, treatment, and disposal system. The leachate collected from Class I solid waste is transferred to the EWRF for further treatment. The second treatment is a collection and treatment system and a stormwater management system that provides reused water for CSEC for cooling and discharge to the Wide Cypress Swamp Wetland Treatment System (WCSWTS)[(211)]. The produced compost from yard waste with appropriate quality for agricultural use is available for public use and collection. A landfill gas-to-energy facility in the OCL transports methane to the CSEC to the coal-fired generation units via an 8 km (5 mile) pipeline[(212)]. The landfill gas produced from the landfill cells is primarily collected for distribution to the CSEC for steam turbine operation and co-fired with coal, while a portion of the landfill gas is flared onsite.

4.3. Urban Food-Energy-Water-Waste FEWW Nexus Framework

The synergistic interactions and interdependencies in the FEWW nexus include: 1) utilization of reclaimed water from EWRF and treated leachate from OCL to CSEC for the cooling towers (water-energy nexus), 2) supply of reclaimed water from EWRF and WCII to EEMUF for irrigation (water-food nexus), 3) solar energy from CSEC to operate EWRF and WCII (energy-water nexus), 4) energy from CSEC supplied to the utility grid for urban farm irrigation, 5) landfill gas from OCL to CSEC for energy generation (waste-energy nexus), 6) food waste from EEMUF to OCL for compost production and landfill gas generation (food-waste nexus). These interactions are visualized in **Figure 15**, where the allocation and utilization of the waste flow from one agent are used as an inflow for another agent, forming a closed-loop system. Further, Table S5[208] helps visualize the relationships in the FEWW nexus.

4.4. System Analysis for an Urban FEWW Nexus

As previously mentioned, the case study of the FEWW nexus was conducted for the urban region of Orlando, Florida, with a population of over 287,000[(213)]. The case study will be divided into four scenarios (cases) for evaluation in order to advance the adaptive integration of technology hubs in different conditions. Case 1 consists of the base analysis, encompassing the food, energy, water, and waste sectors with the corresponding facilities at present mentioned above. Case 2 analyzes the increase in urban agriculture and change with respect to the food sector while maintaining the framework from Case 1. Case 3 builds upon the expansion of urban agriculture from Case 2 based on policy change of land management and proposes an increase in solar energy from the policy implementation of additional incentives for solar PV farms to decrease the carbon and water footprint. Lastly, Case 4 implements a climate change scenario for more stormwater reuse and recycling, including future climate change impact associated with increased rainfall on the given Case 3 condition. According to the Intergovernmental Panel on Climate Change (IPCC), Florida will experience more extreme rainfall events and droughts with 10%-20% rainfall increase projections depending on the emission scenarios[(5)]. In summary, the goal in the progression of the four cases is to address land management, incentivization for solar energy, climate change impact from increase rainfall, observe the sustainable transition of the nexus, and explore the possible tipping point and policy instruments. Thereby, these four cases show a series of planning alternatives for expansion during the next 10-year period. **Table 14** describes the different components in the four scenarios of this study.

Table 14. Case Study Description of the Current Urban FEWW Nexus

Scenario	Analysis	Food Components	Energy Components	Water Components	Waste Components
Case 1	*Base (current condition)*	• Farm sites located in North and North-West Orlando • Area of 2,500 m^2	• Curtis H. Stanton Energy Center (e.g., Natural gas, Landfill gas, Coal, Solar PV)	• Eastern Water Reclamation Facility (EWRF) • Water Conserv II Water Reclamation Facility (WCII WRF)	• Orange County Landfill • Compost Production
Case 2	*Increase in urban agriculture*	• Expansion of urban farm sites in North-East and South-West of Orlando • Area of 5,000 m^2	• Curtis H. Stanton Energy Center (e.g., Natural gas, Landfill gas, Coal, Solar PV)	• Eastern Water Reclamation Facility (EWRF) • Water Conserv II Water Reclamation Facility (WCII WRF)	• Orange County Landfill • Compost Production
Case 3	*Increase in renewable energy (solar)*	• Area of 5,000 m^2	• Curtis H. Stanton Energy Center (e.g., Natural gas, Landfill gas, Coal, Solar PV)	• Eastern Water Reclamation Facility (EWRF)	• Orange County Landfill

Scenario	Analysis	Food Components	Energy Components	Water Components	Waste Components
			• Inclusion of additional solar PV farm near Conserv II	• Water Conserv II Water Reclamation Facility (WCII WRF)	• Compost Production
Case 4	*Climate change impact + inclusion of stormwater reuse*	• Area of 5,000 m^2	• Curtis H. Stanton Energy Center (e.g., Natural gas, Landfill gas, Coal, Solar PV) • Inclusion of additional solar PV farm near Conserv II	• Eastern Water Reclamation Facility (EWRF) • Water Conserv II Water Reclamation Facility (WCII WRF) • Stormwater reuse/recycle (e.g., storage tanks) area of 40,000 m^2 or volume of $1.60(10)^8$ L	• Orange County Landfill • Compost Production

4.5. Methodology

This study comprises a series of integrative analyses, as demonstrated by the flowchart in **Figure 16**. First, SDM is performed to address the material and energy flows in the food, energy, water, and waste sectors in which subsequently the circular economy (address many resource links) and sustainability and resilience can be explored. The involvement of cost-benefit-risk tradeoff proceeded by policy and governance, and lastly, multicriteria decision making is conveyed.

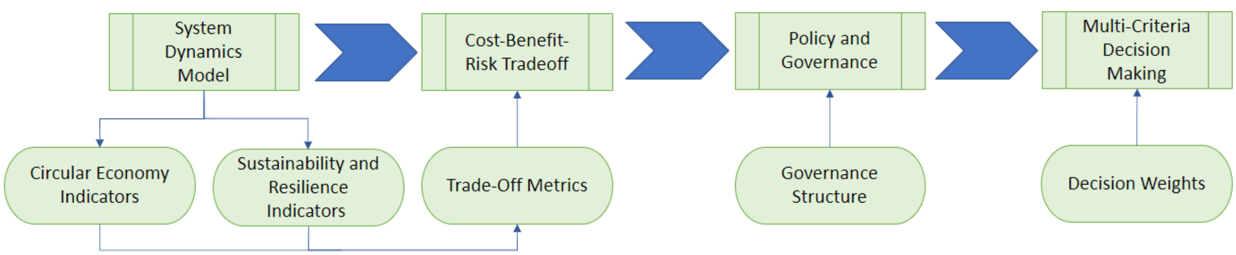
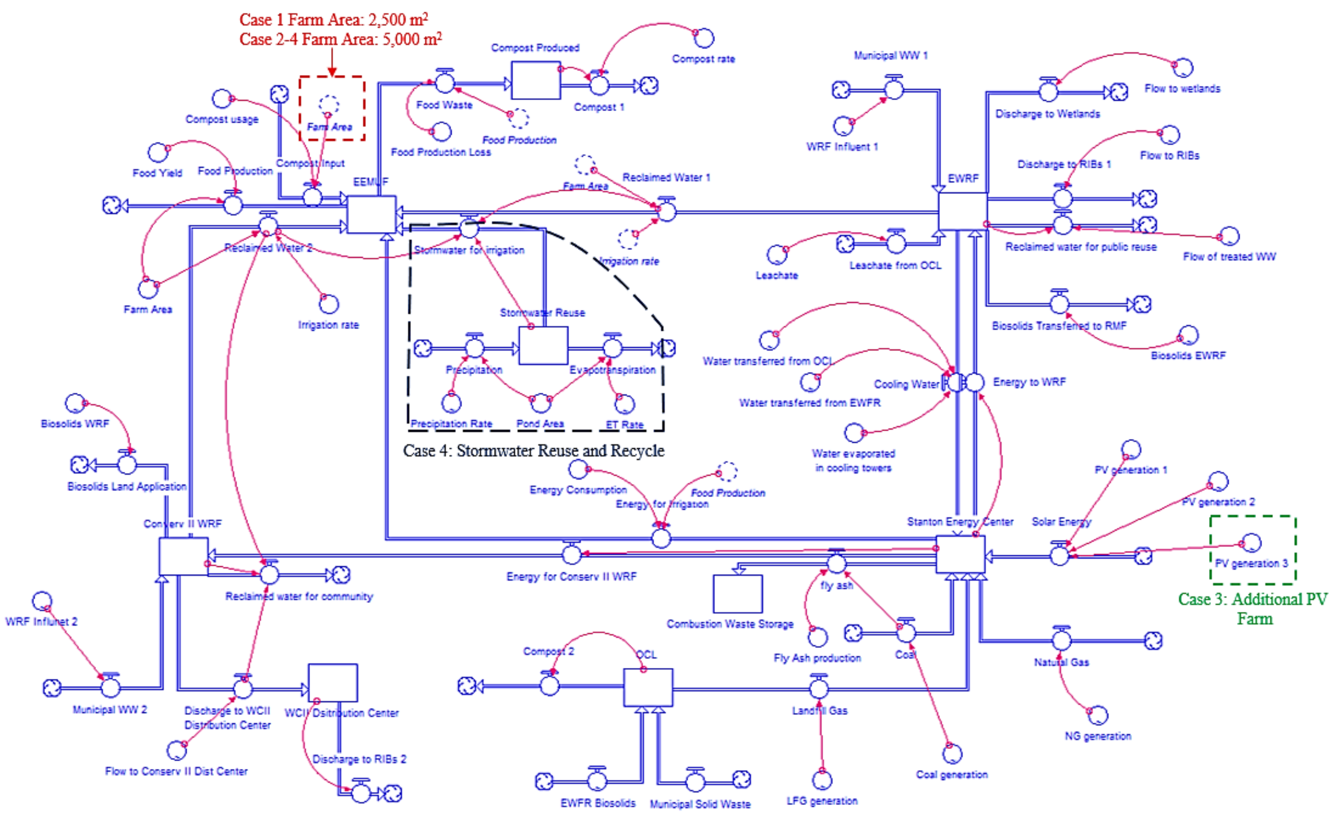


Figure 16. Flow chart of methodology components in this study

4.5.1. System Dynamics Modeling

The SDM portraying the material and energy flows in the food, energy, water, and waste sectors in the urban FEWW nexus utilize STELLA 10.0 software. The SDM supports multi-agent modeling analysis, a multi-stage planning process that corresponds to the four-scenario analyses of Cases 1, 2, 3, and 4 to visualize urban agriculture, climate change impact, and the effect on urban areas sustainability. Variables such as food production, food waste, irrigation water demand, reclaimed water supply, and energy generation is considered and explored in the technology hub integration modeled by stocks and flows to reflect resource interdependencies and interconnections. The SDM inputs and relevant data are summarized in Table S6-S10[203]. The interactions between the five key entities in the nexus from which the associated material and energy flows are visualized in **Figure 17**. The proposed life cycle is a 12-month period in which a monthly time scale is applied in the SDM.



EEMUF: East End Market Farm, OCL: Orange County Landfill, EWRF: Eastern Water Reclamation Facility, Compost Rate:Percent of food waste used for compost production, Compost 1: Compost from urban farms, Compost 2: Compost from OCL, Biosolids EWRF: Biosolids from EWRF, Biosolids WRF: Biosolids from Conserv II, WRF Influent 1: EWRF influent, WRF Influent 2: Conserv II influent, Municipal WW1: EWRF wastewater flow, Municipal WW2:,Conserv II wastewater flow, LFG generation: Landfillgas generation, NG generation: Natural gas generation

Figure 17. System Dynamic Model for a) Case 1 (base), Case 2 (expansion of urban agriculture-boxed box), Case 3 (increase in solar PV farms-green), and Case 4 (stormwater reuse and recycling-blue box).

The input variables employed in the SDM were obtained from real-world data or conservative assumptions. According to the USEPA[214], yard trimmings contain 12.1% of the total municipal solid waste generated. Therefore, it was assumed that 90% of urban farm food waste is composted (denoted as compost 1 or food waste compost hereafter), and 10% of the total municipal solid waste received by OCL is yard waste used in the production of compost (denoted as compost 2 or landfill compost hereafter). A 30% food waste produced from the total urban food production was assumed based on the estimate of 30-40% food wasted from the total food supply in the US[215]. Further, the required compost needed per agriculture area was determined as 0.95 kg•m^{-2} (8,500 lb•ac^{-1}) based on the typical range of 0.34-2.24 kg•m^{-2} (3,000-20,000 ton•ac^{-1}) of annual application. A summary of all the input variables employed in the SDM for the different agents is included in Supplementary Information Tables S3-S7[203].

4.5.2. Circular Economy Indicators

The performance of a circular economy can be measured using various indicators that influence economic development: societal behavior, sustainable resource management, and business operations[216]. Societal behavior reflects actions by the community towards a circular economy that includes willingness for recycling/remanufacturing, reuse, and change in consumption attitude towards the disposition of paying more for durability and sharing. Sustainable resource management encompasses several indicators that assess resource demands, decrease in environmental impact, and increase in resource security. Business operations relates to the business models modified for transitioning to a circular economy by following the principle of circularity and a closed-loop system. Further, a total of 10 indicators corresponding to the areas of production and consumption (e.g., food waste, self-sufficiency of raw materials), waste management (e.g., recycling rates), secondary raw materials (e.g., use of recycled materials to replace raw materials), and competitiveness and innovation (e.g., investments for innovations) are used by the European Commission to address circular economy[217].

In this study, the circular indicators used for system analysis include the evaluation of material and energy efficiency within the nexus, consumption of raw materials versus secondary materials (byproducts), analysis of value from waste, and value from food production. Hence, in each scenario of the case study, the primary evaluation of the circular economy of interest includes: 1) reduction in raw material consumption (e.g., reclaimed water utilization as a substitute for potable water), 2) recycle and reuse (e.g., food waste reuse), 3) production from secondary material (energy from landfill gas), and 4) services (urban food production in the community), as described by **Table 15**.

Table 15. Indicators Used for Assessing Circular Economy in This Study

Indicators	Assessment	Formula	Variables
Reclaimed water utilization	Quantity of avoided potable water demand from reclaimed water use in a community	$RW_{irrigation} = \sum IR_{crop} * A * t$	$RW_{irrigation}$=reclaimed water for irrigation (L•d^{-1}) IR_{crop}= irrigation rate representing water necessary for crop cultivation (L•m^{-2}•d^{-1}) A= area of urban agriculture system (m^{2}) t= time (day)
Food waste reuse	How much food waste is transformed into compost in a community	$FWR = \frac{F_{waste}}{C}$	FWR= food-compost ratio F_{waste}= food waste (kg•month^{-1}) C= compost (kg•month^{-1})
Waste to energy generation	The ratio of waste produced to landfill gas generated in a community	$WTE = \frac{M_{waste} * E_{LFG} * conversion \left(\frac{1\ ton}{907.2\ kg}\right) * 24\ h * 30d}{LFG}$	WTE= waste to energy ratio M_{waste}= Municipal waste (kg•month^{-1}) E_{LFG}= energy produced per 1(10)^{6} tons of landfill waste (MW• mill ton^{-1})* LFG= landfill gas (MWh•month^{-1})

Indicators	Assessment	Formula	Variables
Food production	Local food production available for a community	$F_{production} = \sum F_{yield} * A$	$F_{production}$= food produced (kg•month^{-1}) A= area of urban agriculture system (m^2) F_{yield}= food yield of crops (kg•m^{-2}•month^{-1})

* 0.78 MW• million ton^{-1} (EESI[(218)])

4.5.3 Sustainability and Resilience Indicators

Food, energy, and water indices related to sustainability and resilience help give further insight into the SDM results of the FEWW nexus. In this study, the term resilience describes the irrigation water supply resilience in the water sector corresponding specifically to the reclaimed water infrastructure. In this system, the water resilience index (WRI) is formulated as the ratio between the irrigation water supply demanded by the EEMUF and the total reclaimed water supplied by the water sources, including reclaimed water from EWRF and WCII and stormwater (Eq.(21).

$$WRI = \frac{I_{EEMUF}}{\sum RW_{irrigation}} \tag{21}$$

where WRI is the water resilience index, I_{EEMUF} is the irrigation water supply required for EEMUF, and $RW_{irrigation}$ is the total reclaimed water supplied by EWFR and WCII for irrigation. In this context, food resilience is quantified as a food security index (FSI) for the Orlando population of 287,000 individuals. The food security index is an indicator of whether the urban agriculture system can support the community food consumption with respect to the produce (vegetables harvest), understanding that a healthy human diet encompasses various food staples. Utilizing the 2003 World Health Organization's guideline recommendation of daily food intake of 4 kg per day per person(96), the FSI can be calculated from the total urban food production (vegetable) in the FEW nexus (Eq.(22).) However, this index is limited to addressing vegetable crops and does not consider other staples in human nutrition, which may not reflect the required daily nutritional value.

$$FSI = \frac{F_{produced}}{F_{intake}} \tag{22}$$

where FSI is the food security index (food consumption ratio), $F_{produced}$ is the total food produced by EEMUF, and F_{intake} is the daily recommended food intake for an adult (4 kg). A value closer to 0 is preferred for WRI, whereas a value greater than 1 is preferred for FSI to demonstrate greater reliability. Although energy resilience can also be explored, evaluating energy sustainability is more appropriate since a more in-depth analysis of energy in the nexus is necessary. Furthermore, the environmental sustainability of the FEW nexus, like its carbon and water footprints, can be evaluated via SDM by employing combustion emission and water consumption factors for the four energy generation fuels to determine greenhouse gas emissions (GHG) and water utilization related to electricity production. Since CSEC is fuel diverse, the contribution of each individual fuel source towards the energy demand for irrigation was considered. Recognizing the energy production of coal, natural gas, landfill gas, and solar power in CSEC, it was determined that coal and natural gas each account for 48.3% of energy production, followed by landfill gas with 2.4% and solar with 1%. The combustion emission factors utilized for bituminous coal, natural gas, landfill gas, and solar power, were 93.28 kg $CO_{2\text{-eq}}$ $MMBTU^{-1}$ (318.36 kg $CO_{2\text{-eq}}$ MWh^{-1}), 53.06 kg $CO_{2\text{-eq}}$ $MMBTU^{-1}$(181.09 kg $CO_{2\text{-eq}}$ MWh^{-1}), 52.07 kg $CO_{2\text{-eq}}$ $MMBTU^{-1}$ (177.71 kg $CO_{2\text{-eq}}$ MWh^{-1})[(219)], and 40 kg $CO_{2\text{-eq}}$ MWh^{-1} [(220)], respectively. The water consumption factors for bituminous coal, natural gas, landfill gas, and solar power were $2.62(10)^3$ $L{\bullet}MWh^{-1}$ (692 $gal{\bullet}MWh^{-1}$), 650.16 $L{\bullet}MWh^{-1}$ (172 $gal{\bullet}MWh^{-1}$), 0 $L{\bullet}MWh^{-1}$ (0 $gal{\bullet}MWh^{-1}$), 7.56 $L{\bullet}MWh^{-1}$ (2 $gal{\bullet}MWh^{-1}$), respectively[(221)]. The carbon emission and water consumption factors for crop production associated with agriculture land use were also considered in the determination of the carbon and water footprints. The carbon emission and water consumption factors associated are delineated in Table S3 and S4. As the possible types of crops cultivated across the EEMUF are numerous (Table S2) [(203)], three crops with highest yield per area (i.e., cabbage, tomato, and carrot) were selected for investigation. To further address another sector of the FEWW nexus, the energy sustainability index (ESI) was evaluated as an indicator of local energy resilience (Eq.(23). The ESI is used to measure sustainable development given the increase in renewable energy sources for energy supply in Orlando (a value closer to 1 is preferred). Considering the residential, commercial, and industrial electricity consumption of $1.8(10)^3$ kWh•month^{-1}, $6.09(10)^3$ kWh•month^{-1}, and $78.6(10)^3$ kWh•month^{-1}[222], respectively, the total energy consumption can be estimated. Here $E_{produced}$ is the energy produced from the CSEC and Solar PV farm, and $E_{consumed}$ is the energy consumed in Orlando (e.g., residential, commercial, and industrial).

$$ESI = \frac{E_{produced}}{E_{consumed}} \quad (23)$$

4.5.4. Decision-Making Evaluation

4.5.4.1. Cost-Benefit-Risk Tradeoff

Exploring cost-benefit-risk tradeoffs between the different FEWW sectors and the corresponding technologies aids in decision-making evaluations for each proposed scenario. Given that public-private partnerships, this merits investigation can have conflicting views on decision-making and risk assessment strategies. Yet, the primary goal for any stakeholder is to minimize cost through cost-effectiveness, minimizing risks, and maximizing benefits, which can be realized through the evaluation of cost-benefit-risk tradeoffs. Therefore, evaluating tradeoffs in terms of food security, energy resilience, and water sustainability is essential. For example, resilience and sustainability address vulnerabilities in the critical infrastructure system that can surface due to environmental changes, like climate change impacts. The cost-benefit-risks tradeoffs associated with the four sectors are described in **Table 16**.

Although open field farming is expected in many suburban agriculture systems, implementing urban farming technologies and methods such as drip irrigation and soil sensors can help minimize resource utilization and maximize crop yield and food resilience. The implementation of renewable energy sources like solar PV and landfill gas and the replacement of traditional nonrenewable fuel sources like coal, natural gas, and oil in energy generation can aid in the reduction of GHG and carbon emissions by transitioning toward more sustainable energy generation. Moreover, energy resilience is achieved by reducing dependence on traditional utility power energy fuel sources. Water resilience and sustainability are promoted through the utilization of reclaimed water from wastewater treatment facilities, in addition to the use of stormwater.

Table 16. Cost-Benefit-Risk Tradeoffs for an Urban FEWW Nexus System

FEWW Sector	Cost	Benefit	Risk
Food: *Urban Agriculture*	•Water and energy costs for irrigation •Fertilizer and compost cost •Continuous maintenance and monitoring	•Increased crop yield if combined with agriculture technologies (e.g., drip irrigation, sensor monitoring) •Food resilience and controllable food supply •Provides access to low access communities (food desert) •Help in water and air quality control •Promote social health (e.g., community gardens) •Bring economic benefits from food supplied to nearby markets	•Production may be affected and damaged by the extreme weather and animals •Non-native crops can be more vulnerable and need more care
Energy: *Coal*	•High capital and O&M costs •Water dependent for cooling the towers of the coal-fired plant	•Affordable energy source •Established energy generation technology and process •Low extraction costs	•Potential for air pollution and GHG emissions •Acid rain

FEWW Sector	Cost	Benefit	Risk
	•Air pollution control and treatment •Water treatment from water used in pollution control		•Extraction can contaminate water sources and environments •Large land use, deforestation, and erosion •Resources depletion •Waste generation
Energy: *Natural Gas*	•Requires collection and storage units •High cost of infrastructure (pipelines)	•Less emission of GHG in comparison to coal •Less electricity cost compared to coal	•Extraction can contaminate water sources from hydraulic fracturing •Highly flammable •Gas leaks
Energy: *Solar PV*	•High installation cost •Energy inverter and storage device	• Low O&M costs •Reduction of GHG and carbon footprint •Transitions into energy resilience • Established technology •Installation and implementation is not restricted	• PV efficiency is region limited •PV material is fragile • Large ecosystem footprint from solar PV farms

FEWW Sector	Cost	Benefit	Risk
Energy: *Landfill Gas*	•Requires collection and storage units	•Reduction of GHG and carbon footprint •Recycling and reutilization of organic materials and waste • Byproduct of natural organic decomposition •Methane burns more efficiently than coal • Low O&M costs	•Production depends on the type of waste and decomposition process in the landfill
Water: *Reclaimed Water*	• High capital and O&M costs •Treatment processes are energy-intensive •Distribution system	•Promoted water reuse •Quality control from regulations for public use •Reduction in potable water dependence •Alternative source of irrigation water compared to surface and groundwater sources •Water resilience and sustainability	•Distribution and use can be restricted by regulations
Water: *Stormwater reuse (wet retention ponds)*	•Initial capital cost	•Low or minimal capital and operation cost •Stormwater quantity and quality control •Reduction in potable water dependence	•Transport of pollutants and sediment from stormwater runoff

FEWW Sector	Cost	Benefit	Risk
		•Alternative source of irrigation water compared to surface and groundwater sources •Groundwater and aquifer recharge	• May need a large area for subsurface storage
Waste: *Landfill (compost)*	• Transportation of compost	• Low O&M costs •Reduction of GHG and carbon footprint •Decreases waste and reduces landfill area needed •Useful for food waste from agriculture utilization •Reduces dependence on fertilizers • Stored and treated in a controlled environment	

4.5.4.2. Multi-Criteria Decision Making

Multicriteria decision-making analysis is a support tool based on possible cost-benefit-risk tradeoffs in a decision-making arena. Evaluating the benefits from the aforementioned four FEWW nexus sectors, including food security, energy sustainability, and water resilience, can be used as variables that influence the criteria of interest. For example, the cost-benefit tradeoffs of the four cases presented in the case study can be compared and analyzed with the technique for order preference by similarity to the ideal solution (TOPSIS) approach[223]. TOPSIS is hence used as a multicriteria decision tool for decision-making analysis that allows the determination of positive (S_i^+) and negative (S_i^-) Euclidian distances (Eq. (25)), where the performance score (P_i) (Eq.(28) helps determine the most ideal solution. First, the vector normalization (Eq.(24)) is performed, followed by the calculation of positive and negative ideal solutions (Eq.(25)) and Euclidian distances (Eqs.(26) and (27)). In this study, the ideal solution is represented by scenarios in the four cases (Cases 1, 2, 3, and 4); the criteria include carbon footprint, water footprint, WRI, FSI, ESI, $RW_{irrigation}$, FWR, WTE, food production (kg), and stormwater reuse (0 = no use, 1 = use).

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{j=1}^{n} x_{ij}^2}} \tag{24}$$

$$A^+ = \{v_1^+, \dots, v_j^+\} \tag{25}$$

$$S_i^+ = \left[\sum_{j=1}^{n} \left(v_{ij} - v_j^+\right)^2\right]^{\frac{1}{2}} \tag{26}$$

$$S_i^- = \left[\sum_{j=1}^{n} \left(v_{ij} - v_j^-\right)^2\right]^{\frac{1}{2}} \tag{27}$$

$$P_i = \frac{S_i^-}{S_i^+ + S_i^-} \tag{28}$$

Here r_{ij} is the normalized score of Case i=*1,2,3*,4, X_{ij} is the score of Case *i* and criterion j=*1,..,8*, v_{ij} is the weighted normalized vector for Case i and criterion j, where $v_{ij} = w_j r_{ij}$ and w_j is the assigned importance of weight for criterion *j,* meaning that the importance assigned to each criterion depends on the priority or significance*;* v_j^+ is the ideal best value based on v_{ij}, and v_j^- is the ideal worst value based on v_{ij}, A^+, A^- is the positive and negative ideal solution, S_i^+, S_i^- is the positive and negative distance between Case i and the overall score for Case i, and P_i= the performance score of Case *i* or its relative closeness to the ideal solution. The significance of the weights for the criterion was assigned in a similar range (0.0985-0.101) since typically, w_j values tend to range between 0-1, where more emphasis was given to the WRI, FSI, ESI, $RW_{irrigation}$, food production, and stormwater reuse, as these indicators help visualize the impact of FEWW nexus on sustainability and resilience.

4.5.5. Policy and Governance in a FEWW Nexus

Posing further challenges and complications in the decision-making process, factors like policy and governance impact the planning, design, and operation of any nexus. This is because regulations and standards are enacted to safeguard and aid the community's interests with respect to risks, contaminants, and the provision of programs that provide financial assistance to promote technology implementations. For instance, water and air pollution treatment and control regulations affect the process of water treatment, wastewater treatment, and even power generation. Further difficulty is presented due to the coexistence of public and private entities; however, this also offers possibilities for partnerships between the two, which can benefit policy implementation. Yet, the fragmentation arising in the food, energy, water, and waste policies causes difficulties in providing coherence in governance and policymaking. Implementing a

FEWW nexus in a community can aid in exploring the feedback between resource productivity and policy decision-making in the food, energy, water, and waste sectors between public and private entities. Therefore, it is possible to enhance policymaking for sustainable development and, conversely, identify stresses or pressures from policy affecting both private and public entities. Policy instruments are used in combination with environmental regulation and standards and the economy to incentivize policy implementation and enforcement. Policy instruments encompass four categories: economic and financial instruments, legal and regulatory instruments, social and cultural instruments, rights-based instruments, and customary norms(224). Economic and financial instruments help change behavior and promote policy implementations via the utilization of taxes, subsidies, and tradable pollution permits. Hence, the interaction between policy and governance impacts both the public and private sectors and, in turn, impacts decision-making and risk assessment.

In Florida, the following incentives for renewable energy applicable for employment include the Federal Solar Investment Tax Credit (ITC), Solar System Property Tax Exemption, and Home Solar System Sales Tax Exemption. The ITC was enacted in 2006 to promote renewable energy, specifically solar energy, providing a 26% tax credit for residential and commercial solar systems up to 2022, dropping to 22% in 2023 and 10% thereafter(225). The Florida solar rebates and tax credit programs extend the ITC policy mechanism to promote solar energy further. The Solar System Property Tax Exemption provides a property tax exemption on the additional home value from the solar system(226), while the Home Solar System Sales Tax Exemption gives a tax exemption for solar system installation, constituting 6% tax for a residential solar system. The Orlando Utilities Commission-Residential Energy Efficiency Rebate Program offers rebates to customers with residential energy-efficient improvements regarding heat pumps, building insulation, high-performance windows, window films, and duct repair. In the water sector, environmental credit trading, such as Water Quality Trading, permits a party with high pollution reduction costs to compensate another party that has less costly pollution reduction[(227)]. For reclaimed water utilization, the treatment criteria follow regulations and statutes from the Florida Administrative Code Chapter 62-610, F.A.C. and Chapter 62-555, F.A.C. The quality standards require the reclaimed water to meet minimum and secondary treatment with a high level of disinfection (62-610.460, F.A.C). Reclaimed water with land application purposes cannot surpass 12 $mg{\bullet}L^{-1}$ of nitrogen or have less than 10 $mg{\bullet}L^{-1}$ total suspended solid before discharge to the application/distribution system (62-610.510, F.A.C). Similarly, the Florida Pollutant Tax enforces a tax on pollutant production under the categories of non-petroleum-based products, petroleum-based products, and perchloroethylene[(228)]. The implementation of water procurement taxes in Florida aims to reduce environmental impacts on Florida's spring water supply by taxing public water systems water extraction at a rate of \$0.033 L^{-1} (\$0.125 $gallon^{-1}$). This revenue is utilized in the Wastewater Treatment and Stormwater Management Revolving Loan Trust Fund for funding water and wastewater treatments. Florida Farm Subsidies are also provided for agriculture in areas related to sugar, cotton, peanut, livestock, corn, dairy, and trees. Each of the subsidies specific to crops include price loss coverage, market assistance, quota buyout, and agricultural risk coverage. Additionally, the environmental quality incentives program (EQIP) provided by the Natural Resources Conservation Service (NRCS) of the USDA provides financial assistance to agricultural producers to preserve surface water and groundwater sources, improve air and water quality, and reduce soil erosion. Further assistance is offered to historically underserved participants to advance the EQIP to help in costs related to material acquisition and contracting[233(229)].

4.6. Results

4.6.1. System Dynamics Modeling

The results from the SDM analysis for the four cases empower the understanding with respect to the different sectoral roles in an urban FEWW nexus in Orlando (Table S11-S13)[(203)]. The different sectoral role is tied to a) food, energy, water, and waste flows (**Figure 18**), and b) explored interrelatedness that provides insight regarding the impact of each on the system. In **Figure 18**, the flows and relations include reclaimed water used for irrigation in the EEMUF for food production, fuel types (e.g., solar, natural gas, etc.) used by the CSEC for energy generation, reclaimed water provided for cooling towers of the CSEC, and OCL yard waste used for compost production. The blue color represents flows to CSEC for energy production. The orange color represents reclaimed water flow used for energy generation, and the dark green color signifies reclaimed and irrigation water supplied for food production, the light green color represents landfill compost, and the purple color represents the waste flow for compost byproducts. Although Cases 1, 2, and 3 may have the same food, energy, water, and waste components, there are distinctions with regard to changes in urban agriculture or renewable energy production according to the specific case. The structure of the interconnections visualized in **Figure 18** (**a, b, c**) is similar; however, there are differences in the annual amount of food production, food waste, food waste compost, and solar energy. A distinction is noted in the food production, as it increases from Case 1 ($1.06(10)^5$ kg) to Case 2 ($2.12(10)^5$ kg) (**Figure 18** (**a**) and **Figure 18** (**b**)), whereas it remains unchanged for Case 3 and Case 4. Similarly, both food waste and food waste compost increase from $3.17(10)^4$ kg and $3.49(10)^4$ kg to $6.35(10)^4$ kg and $5.71(10)^4$ kg, respectively, in Cases 1 and 2, and remains the same for the rest of cases. An increase in solar energy generation from $1.76(10)^6$ MWh to $2.65(10)^6$ MWh starting in Case 3 and continuing for Case 4 is noted in

Figure 18(c). Case 4 is described by **Figure 18(d)**, wherein it incorporates stormwater as an additional irrigation source. Here the stormwater provides an additional $1.16(10)^8$ L of irrigation water to the EEMUF, while the food, energy, and waste flows are unchanged compared to those in Case 3.

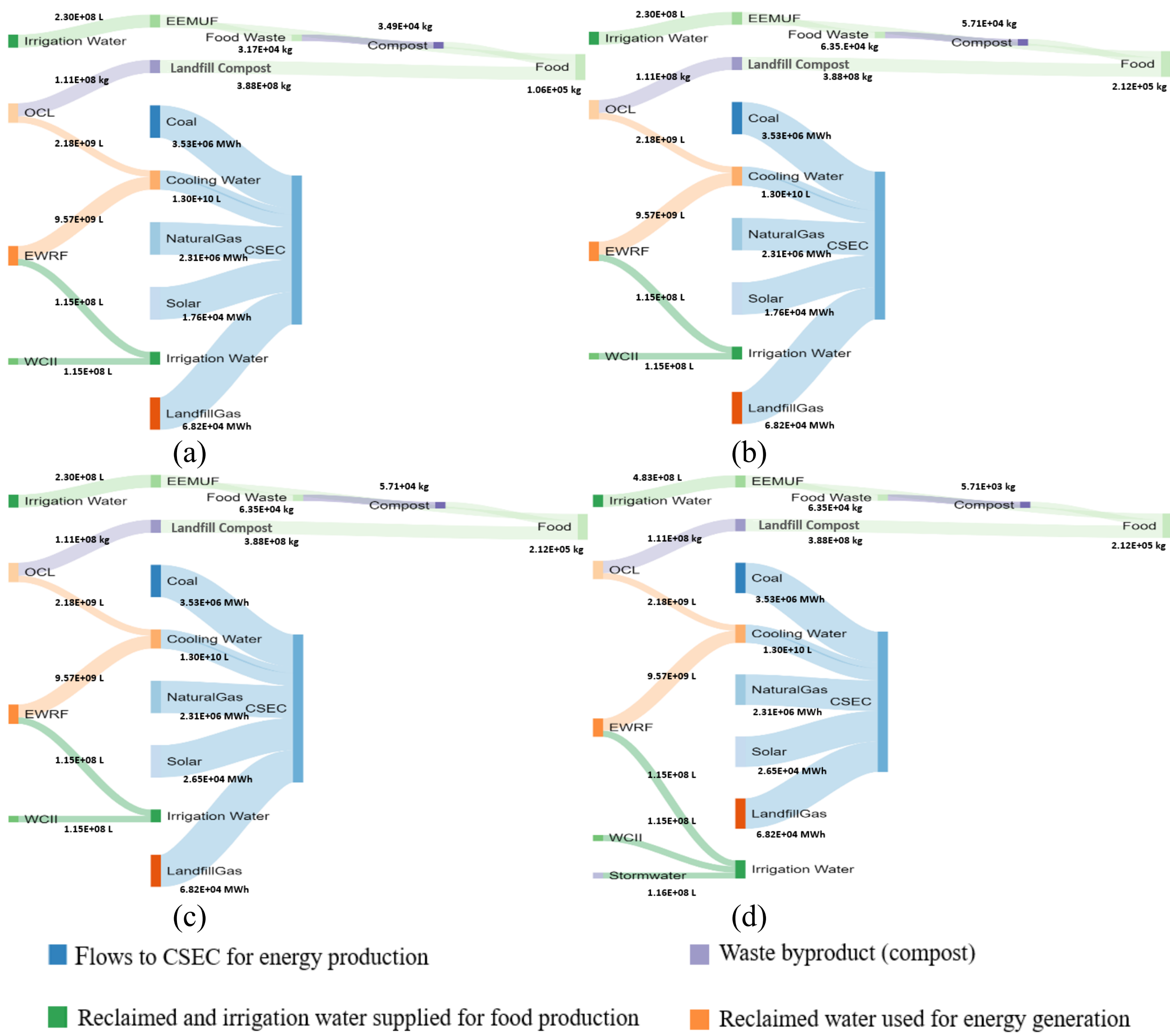


Figure 18. Sankey diagram of fundamental framework flows in a FEWW nexus (a) Case 1, (b) Case 2, (c) Case 3, and (d) Case 4

4.6.2. Urban Agriculture

The SDM results for Case 1 show a food production of 105.8 tonnes•year^{-1}, compost utilization of 0.198 tonne•yr^{-1}, and food waste generation of 31.7 tonne•year^{-1}. The compost produced by the food waste accumulated in the EEMUF is 28.53 tonne•yr^{-1}. A similar relation is observed for Case 2, where the available area specified for urban agriculture is increased, and the food production, compost utilization, food waste generation, and food waste compost production are 211.60 tonne•yr^{-1}, 0.397 tonne•yer^{-1}, 63.48 tonne•year^{-1}, and 57.07 tonne•yr^{-1}, respectively. Since the values for urban agriculture do not change for Case 3 and Case 4, these variables remain the same.

4.6.3. Energy Generation

According to the CSEC energy database, the monthly energy generated from the two solar PV farms operated by the CSEC, based on 2019 energy data, was determined to be $1.47(10)^3$ MWh. In Case 1, when considering the monthly average electricity demand of providing irrigation to the urban farms of 0.67 MWh, with an annual demand of 7.37 MWh, it is noted that the energy generated from the solar power is sufficient to cover the urban farm system demand independently given that the energy generated from the two solar power plants is $1.47(10)^3$ MWh per month or $1.76(10)^4$ MWh per year. However, it is noted that the annual energy produced from the landfill gas ($6.82(10)^4$ MWh) is higher than the energy from the PV farms ($1.76(10)^4$ MWh); this demonstrates the impact of the integration of OCL in the FEWW nexus, as it provides a fuel source to the CSEC for energy generation. Yet, the primary fuel source for energy generation in CSEC remains as bituminous coal ($3.53(10)^6$ MWh), followed by natural gas ($2.31(10)^6$ MWh). In Case 2, where the urban farming sites are expanded, the energy demand for irrigation increases to 1.34 MWh per month and 14.74 MWh annually. This relation remains the same for Cases 3 and 4, where the area for urban agriculture is maintained as 5,000 m^2. Similarly, the coal, natural gas, and landfill gas energy generation remain constant for Cases 3 and 4; however, the annual solar energy generation increases in Case 3 to $2.65(10)^4$ MWh due to the additional PV farm. This solar energy generation is maintained in Case 4. Additionally, the total annual cooling water supplied to the CSEC is $1.30(10)^{10}$ L; this considers the water obtained from EWRF and OCL ($2.89(10)^9$ L), and the water lost in the evaporation process in the cooling towers.

4.6.4. Reclaimed Wastewater Management

According to the irrigation rate for crop cultivation based on the selected categories of crops maintained in the EEMUF, the reclaimed water necessary for irrigation is $9.60(10)^6$ L•month^{-1} for an area of 2,500 m^2 (Case 1). For Case 1, the quantity of treated reclaimed water available for public use by the EWRF and the WCII is a monthly average of $1.71(10)^9$ L and $8.46(10)^8$ L, respectively, which is sufficient to provide the reclaimed water to the EEMUF for irrigation and still have effluent to provide for community use and discharge to RIBs. If $9.60(10)^6$ L•month^{-1}is proposed for allocation by each water reclamation facility, on average, the EWRF would discharge an average of $1.56(10)^7$ L to the RIBs for groundwater recharge, $1.71(10)^9$ L for community reuse, and $9.57(10)^9$ L to CSEC for the cooling towers. Similarly, the WCII can provide an average of $1.07(10)^9$ L to the RIBs for groundwater recharge, $8.46(10)^8$ L for community reuse, and $1.20(10)^9$ L to the WCII Distribution Center in Case 1. For Case 2, due to the expansion of urban agriculture, the irrigation water demand increases to $1.92(10)^7$ L•month^{-1}. Although the discharge of EWRF to the RIBs and EWRF distribution to CSEC remain unchanged, the reclaimed water for community reuse reduces slightly from $1.71(10)^9$ L to $1.70(10)^9$ L. The discharge to the RIBs and the WCII distribution center remains the same for WCII, with only a slight decrease in the quantity of reclaimed water for community reuse from $8.46(10)^8$ to $8.37(10)^8$ L observed. These observations are also noted for Case 3 and Case 4 because the expansion of the urban agriculture system is consistent across Cases 2-4. The decrease in the available reclaimed water for community reuse can be attributed to the increase in irrigation water demand by the EEMUF. The annual quantity of treated reclaimed water distribution by the EWRF and WCII facilities is depicted in **Figure 19**, with a distinction between the different reclaimed water uses.

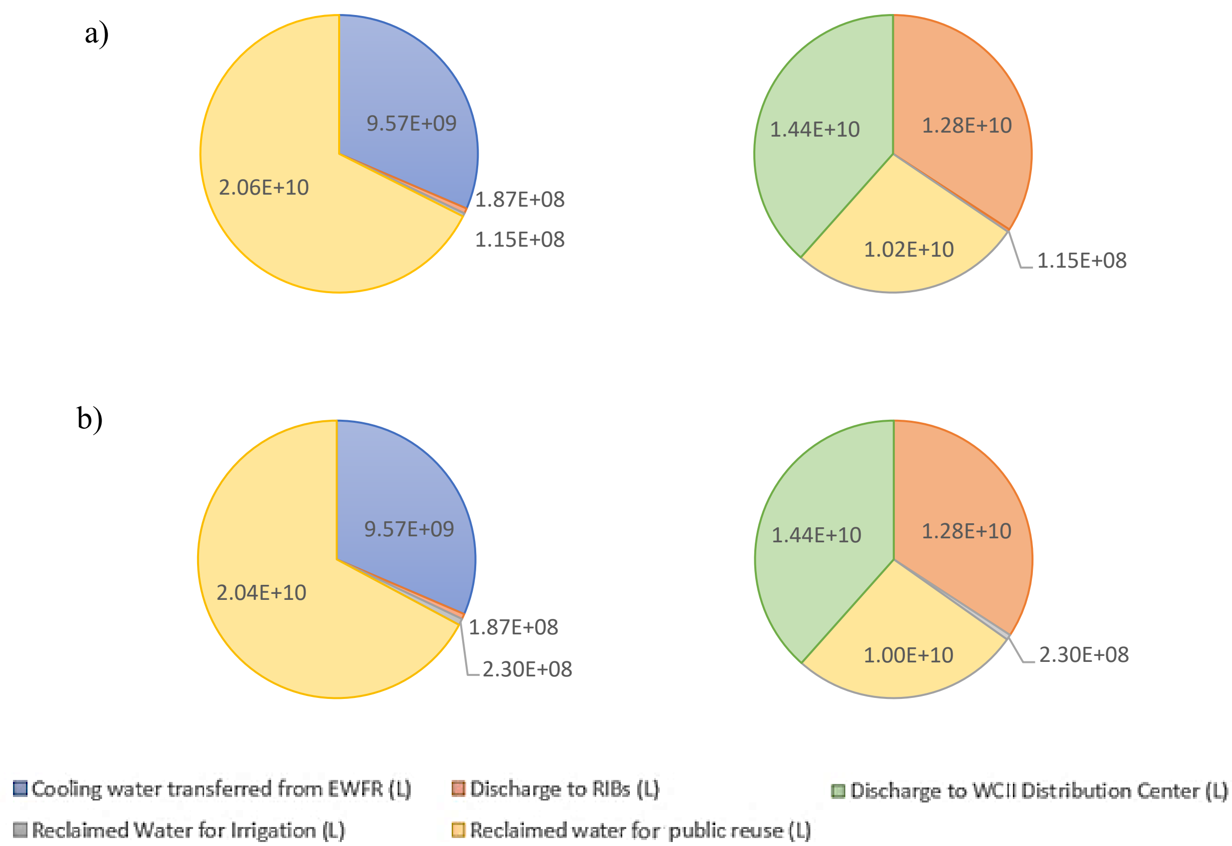


Figure 19. Distribution of Reclaimed Water from EWRF and WCII in a) Case 1, and b) Case 2,3,4

4.6.5. Solid Waste

There are various components and flows in the waste sector, including food waste, biogas generation, compost production, leachate generation, and biosolids from wastewater treatment. The waste accumulated in the landfill cells belonging to municipal waste, including yard waste, can generate landfill gas, used for energy generation by the CSEC. The compost resultant from the components of yard waste of the municipal solid waste transported to the OCL was determined as $3.88(10)^8$ tonne•y^{-1} for all four cases. Further, the OCL facility produced an average of $3.14(10)^8$ L of leachate monthly and $3.77(10)^9$ L annually, which is transported to the EWRF for treatment. Since the OCL produces sufficient landfill compost to supply the community, the EEMUF can also utilize this resource (landfill compost) for urban farming in congruence with the food waste compost. Further, the Class A biosolids generated by EWRF sludge for land application were determined as 117.25 tonne•y^{-1} for all four cases. Currently, these biosolids are land applied at specific locations by the facility and not for public use. The general relation and trend of the annual food production, landfill compost, and food waste compost use are shown in **Figure 20**, which depicts the correlation between the three.

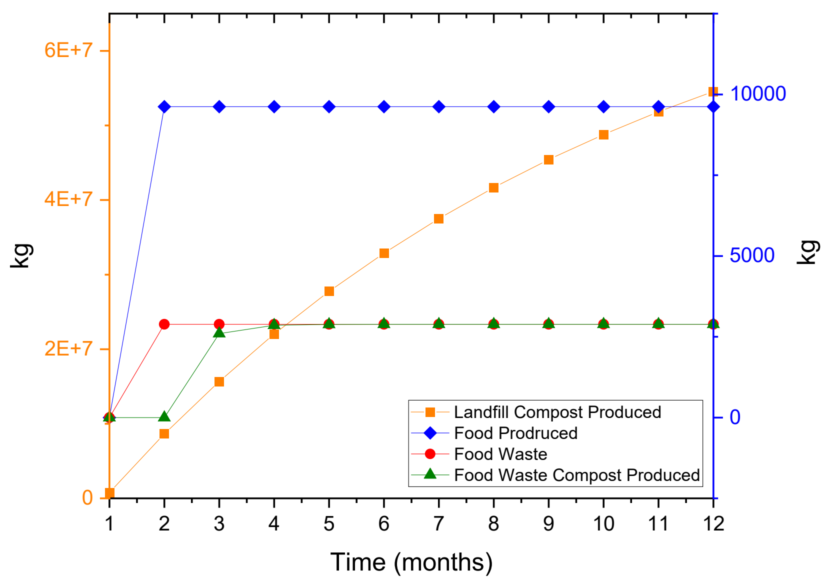


Figure 20. The overall relationship between urban food production, food waste compost production, and landfill compost use in all cases (**left axis**: Landfill Compost Produced; **right axis**: Food, Food Waste, and Food Waste Compost Produced)

4.5.6. Circular Economy Analysis

The effect of the FEWW nexus on the circular economy can be explored using sustainability indicators. Primarily, the services and resource management of the FEWW nexus in the four sectors can be assessed in a community-scale circular economy (Orlando, FL) based on **Table 15**. This includes food production, reclaimed water for irrigation, renewable energy sources (e.g., solar and landfill gas), and stormwater reuse. The surface water and potable water utilization avoided from treated reclaimed water are measured as the total water used by EEMUF for crop irrigation ($RW_{irrigation}$). Thus, the avoided demand on potable waste or the reduction of raw material consumption is proportional to the reclaimed water allocated for irrigation of $1.15(10)^8$ L•y^{-1} for Case 1, and $2.30(10)^8$ L•y^{-1} for Cases 2, 3, and 4. Furthermore, the demand for potable water can also be avoided with stormwater reuse, as in Case 4, where $1.16(10)^8$ L•y^{-1} is available.

4.5.7. Sustainability and Resilience

The environmental indicators are the carbon footprint expressed as greenhouse gas emission (kg $CO_{2\text{-eq}}$) and water footprints (L) shown in **Table 17**. Summary of Sustainability and Resilience Indicators in This Study. These indicators were implemented in the SDM analysis by utilizing emission and water use factors. **Figure 21** shows the SDM for this carbon and water footprint analysis in the proposed life cycle (one year). The carbon and water footprints increased from Cases 1 to Case 2 onwards; this is a response to the increase in the urban farming land starting from Case 2-4. It appears that the use of solar energy resultant from the addition of another solar PV farm by the CSEC in Cases 3 and 4, does not greatly impact the carbon and water footprints as these remain constant from Case 2 to Case 4. Similarly, the increase in the water footprint is due to the increase in reclaimed water utilization by EEMUF for food production to accommodate the increase in land and crop cultivation. The WRI remained stable at 0.50 for Cases 1, 2, and 3 and only decreased slightly to 0.48 in Case 4. This demonstrates the impact of stormwater reuse as an additional source of irrigation water for urban agriculture. Stormwater reuse transitioned the WRI closer to its desired value, as a value close to 0 is preferred. Yet, increasing the quantity of irrigation water supply by the WRFs would increase water reliability. On the contrary, the food supply index (FSI), corresponding to food resilience, increased from 0.09 in Case 1 to 0.18 in Cases 2, 3, and 4. This increase is preferred, as it suggests more food availability from production in comparison to consumption and results from the incrementation of the urban agricultural area that was implemented beginning in Case 2. Since the energy sustainability index (ESI) increased slightly from Case 1 and Case 2 to Case 3 and Case 4, these differences demonstrate the possible influence of additional solar energy generation used by CSEC.

(a)

(b)

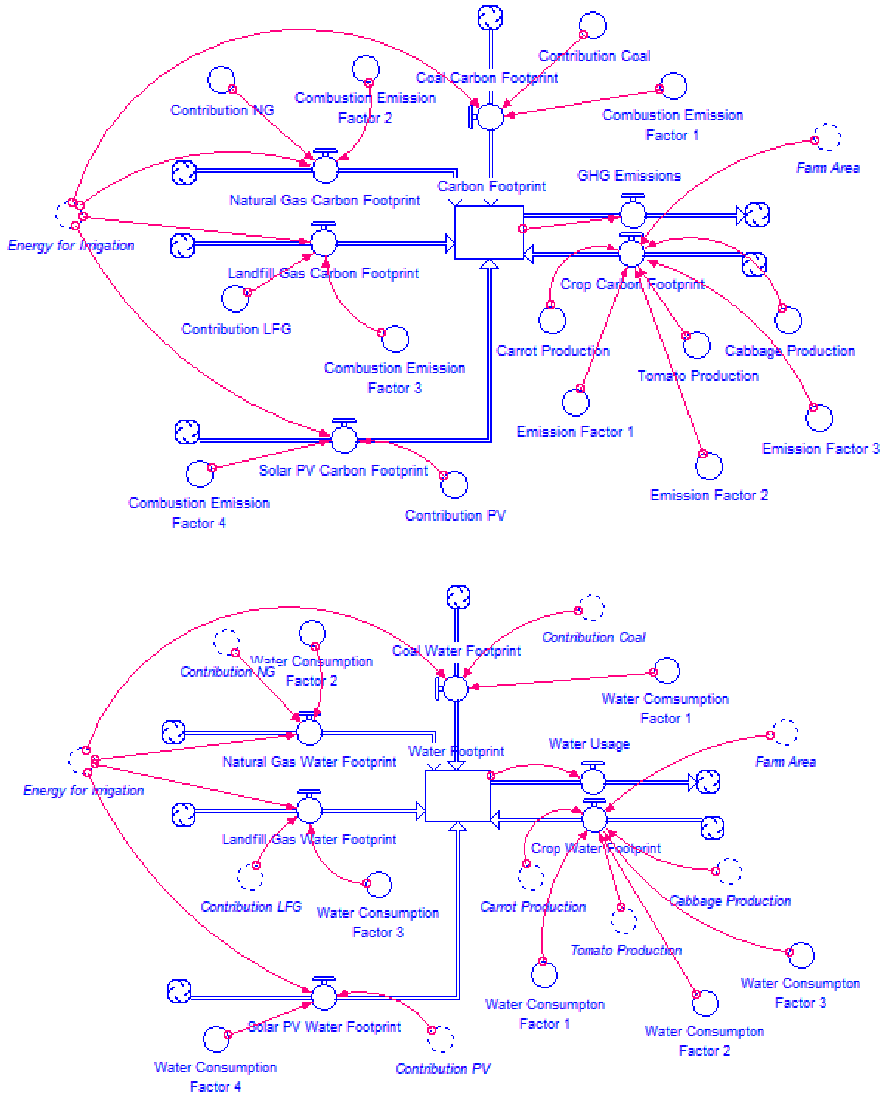


Figure 21. (a) Carbon Footprint and (b) Water Footprint SDM

Table 17. Summary of Sustainability and Resilience Indicators in This Study

Scenario	**Carbon Footprint (kg $CO_{2\text{-}eq}$)**	**Water Footprint (L)**	**Water Resilience Index (WRI)**	**Food Supply Index (FSI)**	**Energy Sustainability Index (ESI)**
Case 1	$1.31(10)^6$	$1.51(10)^7$	0.50	0.09	0.809
Case 2	$2.63(10)^6$	$3.03(10)^7$	0.50	0.18	0.809
Case 3	$2.63(10)^6$	$3.03(10)^7$	0.50	0.18	0.810
Case 4	$2.63(10)^6$	$3.03(10)^7$	0.48	0.18	0.810

4.7. Discussion

4.7.1. Synergies and Interactions in Urban FEWW Nexus

The synergies and interlinkages in the FEWW nexus provide insight regarding the factors that are impacted in changing conditions. The visualization in SDM illustrates that the urban farming system is the primary sector in the nexus that is influenced and affected by the various interconnections and flows from the energy, water, and waste sectors. That is, the EEMUF does not directly impact facilities in the other FEWW sectors but instead relies on the supply of water, energy, and even landfill compost for operation. In the urban farming system, the food generated by EEMUF represents available fresh food, which can offset the need for purchasing food from external food sources. However, since the EEMUF produces sufficient compost, the EEMUF can transition from purchasing compost from an external company such as Monterey Mushrooms, Inc, and utilizing the locally produced compost from the urban agriculture system. If sufficient food compost is made by the EEMUF or acquired from the OCL, stormwater best management practices (BMPs) can be coupled with compost as a form of medium implement for further nutrient abatement for stormwater quality control. The compost BMP technologies that can be contemplated include compost filter socks designed for protection of inlets and stormwater drains, stormwater pollution control, low impact developments (LIDs)[230], compost blankets for erosion and stormwater control[231], and compost filter berm for erosion control[232].

In the energy sector, the energy demand from the urban agriculture system is supplied by CSEC, which utilized four fuel sources. Yet, when distinguishing the energy generated from the individual fuel types, the EEMUF energy demand can still be supplied solely by landfill gas. Since the generated solar energy is sufficient to maintain the irrigation for the farming sites, the addition of another solar PV farm, as in Cases 3 and 4, will further improve the energy resilience of the nexus and help the CSEC move away from nonrenewable energy sources and decrease its dependence on coal and natural gas. Moreover, an increase in landfill gas generation from the OCL can also enable CSEC to transition into using a more significant percentage of renewable fuel sources, as the monthly and annual energy generated from the landfill gas was observed as $5.69(10)^3$ MWh and $6.82(10)^4$ MWh, respectively.

The synergistic relationship between the food and energy sectors can be further extended to the water sector. The water reclamation facilities (WRFs) facilitate the reuse of treated wastewater effluent for different purposes such as irrigation, public reuse, and the use in cooling towers of CSEC. The irrigation water demand in the system is supplied by both WRF; if there is an interruption of supply from one facility, the other facility can still meet the irrigation demands of EEMUF. However, the employment of the stormwater reuse system in Case 4 serves as an additional layer of reliability in the system with regard to irrigation water supply, as it has the capacity to supply an average of $8.46(10)^6$ L•month^{-1}. With the aid of BMPs, the stormwater reuse system can reduce the stress on the WRFs for irrigation water and free more reclaimed water for public reuse and aquifer recharge via RIBs and the water supply for CSEC if this demand were to increase.

Since food and water flows are interconnected, the quantification of water and food resilience indices supports the implementation of urban agriculture and reclaimed water. Although the water and food resilience indicators used to quantify resilience for the FEWW nexus may not vary from case to case, the addition of irrigation water supply from the stormwater system to the existing irrigation water supplied by the WRFs in Case 4 lowered the WRI, which is preferred. However, the WRI of 0.50 still suggests water resilience, as the total irrigation water supply is twice the irrigation water required by the EEMUF. The increase in FSI in Case 2 supports the claim of food resilience since there appears to be greater food production than food consumption, according to the assumptions made on the community population and utilizing the recommended daily food intake for an adult. Further, an in-depth analysis of the nutritional value of the harvested food will need to be considered to address adequate nutrition. These findings are crucial if the community wants to be self-sustained in the case of increased resource depletion, which would result in increasing resource competition in the procurement of water and food. However, it should be noted that for the community to be fully self-sustained, further aspects of the food supply have to be considered, provided that the possible crops harvested in the EEMUF are limited. Yet, a disadvantage of having self-sustained and local production without proper redundancies is a lack of protection against disruptions that can interrupt the food supply chain. Currently, the urban agriculture system in place aims to reduce food insecurity. Moreover, the competition between potable water sources can be reduced by implementing reclaimed water and stormwater. Additionally, if reclaimed water demand for RIB and groundwater discharge increases, the stormwater reuse system can be enlarged to support irrigation for urban agriculture. The cost savings from reclaimed water utilization versus public water supply (e.g., potable) can be calculated. Cost-saving can be accomplished by using reclaimed water instead of potable, as the reclaimed water rate schedule includes retail ($0.89 per 1000 gal) and bulk pressure service ($0.69 per 1000 gal)[(233)].

Moreover, the circular economy in the FEWW nexus is tied to the utilization of secondary materials and byproducts influenced by the interconnections in the system, which can be evaluated using factors like food waste reuse (FWR) that represents the relationship between food waste and compost generated by the EEMUF. It is noticeable that the average FWR ratio was 0.91 for all four cases, indicating a linear trend between the food waste produced by the urban farms and the compost generated. This demonstrated an almost closed system in urban agriculture between food waste and compost generation. On the other hand, the average WTE ratio was determined as 0.04, which suggests the level of anticipated landfill gas recovery based on municipal solid waste in this study.

4.7.2. Interactions of Policy, Cost-Benefit-Risk Tradeoff, and Decision Making

Governance structure and function might affect sustainable development as a range of policy instruments may be designed to aid in urban sustainability in the food, energy, and water sectors for sustainability transitions. Investment in innovations and technology development is one of the primary strategies besides economic incentives for promoting and advancing sustainable development. The incentives for renewable and clean energy, such as the ITC, incentivize the expansion of solar energy. The implementation of solar PV is beneficial in areas that receive sizeable solar irradiation, such as Florida, which can take advantage of this resource to produce solar energy. Investment in technologies for stormwater treatment like BMPs and LIDs is also crucial in sustainable development. Stormwater management for reuse is considered, given that stormwater can be viewed as a sustainable resource for mitigating water scarcity due to climate change impact. Policy instruments related to urban farming subsidies are also important in Florida given its involvement in agriculture production, such as the implementation of EQIP, which promotes resource preservation and sustainability through financial assistance to agricultural producers. Support for urban agriculture is also provided, as the benefits related to general urban agriculture practice are substantial and target all three aspects of urban sustainability (social, environmental, and economic). The implementation of alternative sources for irrigation, like reclaimed wastewater and stormwater, also provide various environmental benefits. The high capital and O&M costs related to reclaimed wastewater reuse are unavoidable costs that WRFs incur to ensure adequate pollution control and wastewater treatment. However, a cost-benefit-risk assessment may be necessary to understand the implications before proceeding to implement a policy that promotes technologies and processes that influence the FEWW sectors.

From **Table 17**, the benefits of utilizing solar PV for energy generation compared to other conventional energy sources are significant, as are the costs and risks of using coal for energy generation. As renewable energy technology continues to evolve, the capital cost of the solar system (integrated with energy storages systems) will continue to drop, which makes the direct cost of renewable energy comparable to, or even cheaper than, energy provided by the regional utilities. In addition, we should note that PV-module-based solar energy systems can be easily installed and operated in a decentralized manner. These decentralized systems can improve the reliability of energy supply, thus avoiding the cost of energy interruption, which can be treated as a large portion of indirect costs that can be avoided by deploying decentralized energy systems. On the other hand, regional power plants usually resort to long-distance transmission and distribution lines to meet the load demand of users, which causes a significant portion of energy loss; however, the utilization of decentralized energy systems can significantly reduce the energy loss due to transmission and distribution since they are generally installed close to the load center. Utilizing distributed renewable energy harvesting methods such as solar photovoltaic can also minimize the investment of building or updating the energy transmission and distribution infrastructures, making it more competitive than merely procuring energy from regional power utilities.

To have more clarity in the planning and design of the infrastructure, the decision-making approach is preferred. Multicriteria decision-making use of TOPSIS can aid in the decision-making and selection process to determine the most appropriate case design in the case study. The alternative solutions represented by the four cases were assessed to determine the most ideal solution according to the closeness of its performance score (P_i) to 1. When considering substantiality and resilience indicators (carbon and water footprints), circular economy indicators (WRI, FSI, ESI, $RW_{irrigation}$, FWR, WTE ratio, stormwater reuse), and urban agriculture food production with specified weights, the most appropriate alternative can be determined, as described by **Table 18**. The interest in the decision-making selection affects the weights assigned to the different criteria previously mentioned. As such, Case 4, encompassing stormwater reuse in the FEWW system, was selected as the most appropriate alternative for FEWW nexus design, with a tie for Case 3 and Case 2. However, if considering the benefits from increasing renewable energy to reduce the use of nonrenewable energy sources with energy sustainability, Case 3 is suggested as the better preferred option between the two cases.

Table 18. TOPSIS Multicriteria Decision Making Results

FEWW nexus solutions	S_i^+	S_i^-	P_i
Case 1	0.112	0.039	0.256
Case 2	0.108	0.049	0.310
Case 3	0.108	0.049	0.310
Case 4	0.039	0.112	0.744

4.7.3. Climate Change Impact

The climate change impact on the urban community can be evaluated according to the stormwater data acquired from the SDM across the four cases. Each case presents progressive change to the base case to visualize a more evolving FEWW nexus during sustainability transitions. For example, the inclusion of stormwater reuse in the nexus in Case 4 can increase the available quantity of treated reclaimed wastewater for community reutilization, which is beneficial if a population increase is expected in the future. The inclusion also adds reliability to the system in case strict regulations for reclaimed wastewater reuse are possibly imposed in the future, hindering the public use of reclaimed wastewater. Currently, in the state of Florida, water management rules ensure the water quality of the reclaimed wastewater is appropriate for land application. Further, the competition for potable water resources can be reduced. If less water is allocated by the WRFs for irrigation and is instead discharged to the RIBs, the aquifers can be recharged to ease the quantity of water pumped for potable water consumption. To curtail environmental impacts with respect to the GHG emissions and reduce the dependency of CSEC on coal and natural gas as primary fuel sources for energy generation, the increase in renewable energy, such as PV farms, can be implemented in addition to landfill gas utilization. In addition, increasing urban agriculture improves community food security and resilience, transitioning the community away from being classified as a food desert and aiding disruptions in the food supply chain during hurricane seasons or extreme weather events. Climate change mitigation can be linked to the diversion of organic waste from landfills, reducing GHG emissions, and providing carbon sequestration from the use of compost and biosolid fertilizer. Despite biosolid fertilizers containing lower percentages of nutrients (e.g., N, P, Ca, S, K, Mg) compared to commercial fertilizers, nutrient percentages of 4.75 % total Kjeldahl nitrogen (TKN), 0.57% NH_4-N, 4.13% org-N, 2.27 % total P, and 0.31% total K were determined[234]. Hence, the land application of composts and fertilizer resultant from biosolids is an alternative to burning or landfilling, which decreases the GHG to be produced in these processes.

4.7.4. Future Work and Limitations

In this study, only one risk factor (e.g., climate change) was considered in Case 4 to address stormwater availability in the future due to the possible increase in rainfall that may be linked to LIDs to address long-term climate change impact and advance our understanding of adaptive transformations of critical societal infrastructures (such as urban farming). The inclusion of precision farming technologies may help innovate the design, operation, and planning of such infrastructure systems under uncertainties such as climate change and land-use policy with land teleconnection effects. Although policy and governance in the nexus system are discussed to evaluate and understand the implications of the impact via policy instruments on sustainable development, a thorough socioecological analysis specific to the Orlando area can be explored further in the future. Despite the practicality of exploring the cost-benefit-risk tradeoff assessment for the four sectors of the FEWW nexus, the decision-making process is still challenging. The comparison yielded insight primarily regarding the costs and benefits associated with the distinct entities in each sector, where it can be observed that the utilization of solar PV and landfill gas is more economically and environmentally beneficial for energy generation. The benefit of reclaimed wastewater and stormwater utilization is also noted since it provides water resilience and food security from urban farming. Although capital and operation costs are significant for WRFs, it is a co-benefit for wastewater treatment as the effluent can be reutilized for many secondary purposes. Future research can be conducted to acquire more data from each facility in the proposed FEWW nexus to conduct a long-term and well-rounded system analysis that can help answer more challenging research questions.

4.8. Final Remarks

Transitioning toward sustainability is paramount in the present era, specifically in metropolitan regions, given the impact and strain of anthropogenic activities on the environment and resource competition. However, challenges in urban sustainability range from sustainable development problems centered on the interactions and behaviors of distinct stakeholders in association with the social, economic, and environmental aspects. As such, the FEWW nexus approach was applied to incorporate more sectors required for sustainability transitions and achieve a more coherent circular economy, as the traditional FEW nexus is not sufficient to advance the understanding of social, environmental, and economic sustainability simultaneously. While the nexus's planning, design, and operation were related to uncertainties such as climate change impact, synergies embedded in the FEWW nexus can transform the urban farming infrastructure to a broader scope. An SDM portraying the food, energy, water, and waste material flows among different sectors in an urban FEWW nexus was thus developed for system analysis in this paper. The proposed FEWW nexus in Orlando, Florida, provided insight regarding the material and energy flows among the distinct entities in the nexus, demonstrating the co-benefit of utilizing reclaimed water and stormwater for potable water reduction and increasing resource conservation. In addition, composting in the EEMUF and producing biosolid fertilizer and landfill gas provides climate change mitigation to some extent. The utilization of the cost-benefit-risk tradeoff and TOPSIS offered further insight for screening the design alternatives in an urban FEWW nexus leading to favor Case 4 as the most preferable one, given that it included greater renewable energy and stormwater reuse. Such sustainability transitions elucidate the essence of environmental convergence opportunities ad more decision-making with social factors can be taken into account.

CHAPTER 5: INTEGRATING SUSTAINABILITY PATTERNS AND GOVERNANCE STRUCTURES VIA CLUSTERING ANALYSIS AND MULTICRITERIA DECISION MAKING FOR URBAN FARMING NETWORK

5.1. Introduction

Urban complexity based on spatial scale varies as cities grow larger through time with changes in urban morphology constrained by urban landscape. In developing countries urbanization is oftentimes associated with economic development promoting the increase of population density in cities[(235)]. Hence, urban sprawl is expected to continue with 68% of the world population projected to reside in urban regions for an additional 2.5 billion people in urban areas by 2050[(1)]. As such, the United Nations (UN) has established 17 UN Sustainable Development Goals (SDGs), where Goal 11 aims for sustainable cities and communities to be resilient, sustainable and safe to achieve balanced social, economic and environmental sustainability[(7)]. Specifically, SDG target 11.3 concentrates on inclusive and sustainable urbanization for sustainable planning and management[(236)]. In congruence, the objective of the UN Food System program is to have an inclusive, sustainable, and resilient network, focusing in sustainable food systems as a necessity by bridging social, economic and environmental sustainable development[(237)] leading to promote autonomy and circular economy. Further, addressing climate change has become a focus tied to urbanism and sustainability. According to the Intergovernmental Panel on Climate Change (IPCC) Sith Assessment Report (AR6), human-induced climate change impacts can affect the frequency and intensity of heavy precipitation, and extreme events of heatwaves, sea level rise, and droughts[(238)]. As such, policy instruments are important to establish and implement to achieve these sustainability goals at the intersection of urbanization, climate change, food security and social equity, as in the case of the European Union (EU). In the 2021 UN Climate Change Conference summit COP26 expressed the urgency of approaching climate change with goals for decarbonization and global net-zero[106]. The EU aims for carbon neutrality by 2050 via implementation of policy for this long-term objective. This strategy comes from European Climate Law, part of the European Green Deal which proposes net zero greenhouse gas emissions for EU countries and carbon neutrality by 2050[107]. However, in order to better understand sustainability, it is important to analyze a suite of sustainable indices/indicators to obtain a quantitative measure that assist in policy decision-making[239, 240].

The principles of urban sustainability entail sustainable metropolitan development in regard to social, economic, and environmental aspects[241]. This encompasses the notion that a city transitions towards more green practices such as renewable energy. The National Academies of Sciences (242) explained that urban sustainability is a multiscale and multidimensional problem that includes the involvement of citizens, public, and private entities, while emphasizing biophysical limits of the planet, interconnection of human and natural systems, urban inequality, and interconnection of cities. Collectively, environmental, social, and economic sustainability interact in various dimensions. The implication of exacerbated population growth triggers the emphasis and concerns on the essential resource security like food availability, specifically in metropolitan regions. Food inequality also plays a part in the geographic regions via food desert identification. The Unites States Department of Agriculture (USDA) Economic Research Service recognized more than 6,500 food desert tracts in the 2000 Census and 2006 facts[200]. Moreover, it has been noted the emergence of 'food deserts' during the past 30 years due to the transition of small local grocery stores to supermarkets[243]. The USDA defines metropolitan areas as a food desert if the community has limited transportation resulting in low access to supermarkets or grocery stores and low income based on census tracts[200]. A low access community is defined by at least 33% of the population or 500 people to live more than 1.6 km (1 mile) from supermarket or grocery store in an urban region. While the 2008 Farm Bill defined a food desert as a region where the access to affordable and nourishing food is limited particularly in lower-income communities[244].

To promote urban sustainability, urban farming practices have resuscitated and garnered increasing interests from public and private entities and policymakers, especially during the era of the pandemics. C40 Climate Leadership Group consist of consortium of 97 cities, primary megacities including Amsterdam, Beijing, Daker, Miami, Rio de Janeiro, and Singapore focused on sustainability with the aim of achieving the Paris Climate agreement goals[245]. Moreover, part of their agenda is to promote urban agriculture targeting food resilience, food self-sufficiency, and local food production according to the 2014 food related targets where around 30% C40 cities have already set these goals[246, 247]. For instance, large urban farming projects are located in 1) Bangkok, Thailand (22,000 m^2) utilizing green roofs and landscape architecture to mimic rice terraces[248], 2) Paris, France (4,000 m^2) employing rooftop farming technologies such as vertical farming[249], 3) Hague, the Netherlands (0.30 acres or 1200 m^2) encompassing green-houses and tilapia farms[250], and 4) Shanghai, China (2.47 acres) promoting vertical farming activities[251]. In the US, urban farming programs exist in various states such as Florida, California, Washington, Texas, Louisiana, South Carolina, and New York. Notably, the largest urban farms in the US are situated in Albuquerque, New Mexico (40 acres), Seattle, WA (8 acres), Baltimore, Maryland (8 acres), and Detroit, Michigan (7 acres)[252]. Nationally, Urban Farm Bureaus have been instated in major urban regions to form a coalition to encourage urban farming practices.

In the context of sustainable cities, urban and peri-urban agriculture contribute to social, economic, and environmental sustainability in congruence with urban resilience. As economy is always interwoven with social and environmental sustainability with priority the environment is the largest factor influenced by economic development that in turn affects social sustainability. This can be evidenced by that environmental decisions are made contemplating the impact of economic efficiency, equity and ecosystem conservation[(253)]. As mentioned by Hodson and Marvin (254), urban ecological security is overlooked as governance is mainly centered in economic development and fails to focus ecological aspects including smart growth, and sustainable development [(246)]. Hence, the implemented governance structure should guide the decision-making arena towards sustainable development. In such a sense, policy making should promote social equity and minimize the externality which in turn achieve economic and environmental sustainability.

The main goal of this paper is to assess if the current urban farming network (UFN) in a metropolitan region can meet the sustainability criteria delineated over the social, environmental, economic dimension and understand how to improve the network governance with priority among those urban farming sites for various social, environmental, and economic concerns. In this paper, the clustering analysis approach is applied to decide how the selected urban farms in the study region that compose an UFN can be implemented in different stages with strategies according to their vulnerability and risk level. Likewise, the scaling up of urban farms should follow some sustainability patterns that can maximize the overall sustainability of the UFN. In this network, the interacting entities also form organizational networks that are dynamically added with governance structures and functions with emphasis on three pillars of urban sustainability. Consequently, the science questions to be explored are: 1) Will urban agriculture have better social and environmental sustainability while confirming economic sustainability in the community via a clustering analysis and multicriteria decision analysis? 2) Can this managerial strategy of UFN be implemented through existing or future governance structure and policy instruments? This paper is organized to first delineate the sustainability indices used for evaluation of clustering analysis and help describe the environmental, social, and economic aspects. It is followed by the governance structure and incentive programs available for food, energy and water sectors. Finally, this discovery is followed by the prioritization of urban farm clusters which is expected to resonate with the final stage of the UFN growth by a more sustainable way.

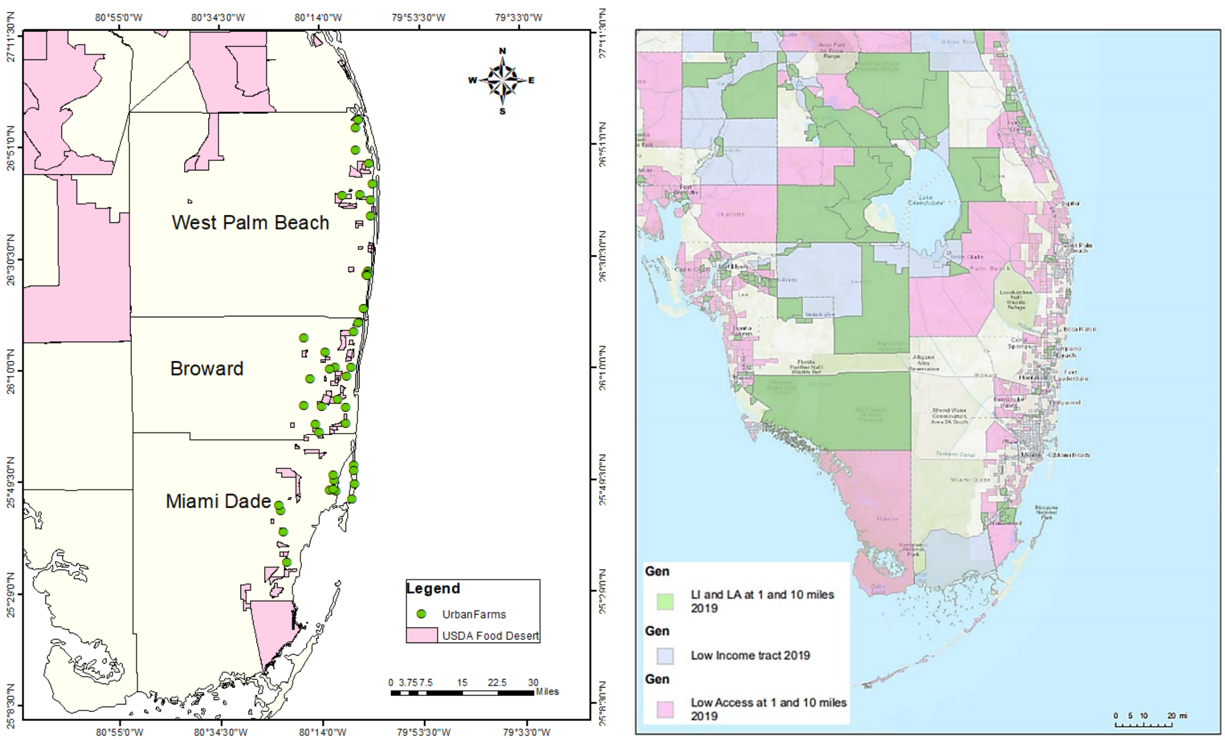
5.2. Methodology

5.2.1. Background

The area of interest encompasses the greater Miami metropolitan region located in Florida, USA consisting of three most urbanized counties in the state: 1) West Palm Beach, 2) Broward, and 3) Miami-Dade. This is also the region that is at the zero ground of climate change in the US, with prominent threats including sea level rise, hurricanes, and flooding. The UFN of interest in this study is comprised of selected sites of 23 identified urban farms (UFs) distributed within these counties, that have been for the most part demarcated as food desert in areas by the USDA (**Figure 21**) (Information pertaining to each UF location can be found in **Tab. B1**). Note that such selection did not cover comprehensively all sites in urban agriculture across the region. For the most part, these UFs consist of community gardens and agricultural facilities aimed at providing healthier food while engaging the community managed by the city supporting different social functions. The urban agriculture facilities such as the Urban Farming Institute and Dania Beach Patch are non-profit organization that provide actionable programs like city sponsored community gardens, urban farm, education, and farmers market[255] whereas Harpke Family Farm provides local foods to restaurants and hotels based on chef partnerships[256].

5.2.2. Governance Structure and Policy Context

Moving away from the traditional governance is the topic of interest which encompasses neoliberal urbanism and neoliberal governance in which policy-making includes minimal government interference and limited governance concentrating on market-oriented policies and self-regulating markets[257]. On the other hand, sustainable growth with respect to New York City High Line park has been looked into urban development and community economic growth[258]. The governance structure in Miami can be somewhat favorable proving more liberty towards individuals participating in urban agriculture at their residence and community as in the case of urban farming market. However, some of these urban agriculture activities have been regulated by the Florida Cottage Food Laws that manage produce marketing in place by stipulating the specific items allowed for sale in a residence with annual gross sales below $50,000 and the approved produce[259].



(a) (b)

Figure 22. Visualization of (a) urban farming sites (UFs) and (b) low income and low food access (USDA[206]) in greater Miami region (Miami-Dade, Broward, and Palm-Beach Counties) (Detail of location and cultivation area in **Table. B1**).

Further, there are also other food policies in place at different governance levels that could affect UFs. For example, fresh cut produce from UFs can only be sold with permitting, processing, and handling for food safety at locations such as farmer's market and food can only be sold within Florida[(260)]. In addition, other federal food policies regarding food safety are regulated by the US Food and Drug Administration and USDA while agricultural land and practices are regulated by Environmental Protection Agency and Department of the Interior. These agencies respond to policies to establish regulations and help curtail public concern, in the case of urban agriculture concerns from reclaimed water irrigation, and landfill compost utilization that could affect food safety and public health. Yet, government funding and political support are crucial for appropriate urban planning strategies responding to a climate change policy such as carbon market or low carbon economy. A further expansion is the application of incentives and subsidies pertaining to agriculture, and energy generation to promote certain energy technologies and specific agriculture crops.

For better understanding, governance is defined by the World Bank (1992) as the "manner in which power is exercised in the management of a country's economic and social resources for development"(261). The scaling-up of the UFN in this study refers to the strategy to use for the prioritization in the gradual addition of UFs. Yet, this growth strategy is influenced by governance structure and policy instruments. Since the interaction and relationship between stakeholders can be described as networks, networked governance structure and function come into play. Network management is crucial to evaluate the structure of network governance that meets the needs of a changing network(262, 263). Network governance structures are employed to tackle challenges via multilateral coordination and involves management and coordination of resources, information and activities of at least three organizations conforming network organization(264, 265). The modes of network governance include self-governed network, lead organization network, and network administrative organization (NAO)(265). Self-governed network is characterized by the distribution of leadership among the members in the decision-making. Lead organization is a more centralized approach that involves one major member to have leadership to manage the network whereas the leadership in NAO is located outside of the network. With long-term evolution, network governance structures can be a hybrid of the three modes. Additionally, polycentric governance can be established where multiple organizations partake in the decision-making arena making up a mixed governance system with multiple governing agents with distributed leadership to promote the potential of group decision-making.

5.2.2.1. Food safety and regulations for small food operations

There are different types of food-related business: cottage food (i.e., home food processing), commercial food processing facility (e.g., retail and wholesale), and (peri) urban farms in the context of urban agriculture. Specific pertinent food safety regulations can be dependent upon the type of business or operation and the nature of food or produce, and regulations or acts in concert with different governance levels (e.g., federal, state). First, at the federal level, the Food Safety Modernization Action in 2011 is the most sweeping reform of the U.S. Food Safety Law since 1938 and is the most comprehensive regulations applicable to farms (including urban farms) produces. It also has other relevant regulations such as preventative controls for human and animal food, sanitary transport rule, and so forth. For example, for preventative controls for human food, there are specific safety regulations on sanitary operations, equipment and utensils, and personnel. The ongoing hazard analysis critical control points (HACCP) is another federal level systematic and preventative system, where food safety is addressed through the analysis and control of biological, chemical, and physical hazards from raw material production, procurement, and handling, to manufacturing, distribution, and consumption of finished product. It breaks down to different types of food, such as Juice HACCP, and seafood HACCP. At the state level (e.g., Florida), the Department of Business and Professional Regulations is the regulatory agency responsible for licensing and regulating business and professionals with examples including food truck, restaurants, farmer’s market, and caterer. Another important agency is the Florida Department of Agriculture and Consumer Services that enforces the federal regulations on operations without interstate commerce and some retails. Cottage food law is another important regulation especially relevant to urban agriculture. In the state of Florida, based on cottage food law, individuals can use their unlicensed home kitchens to produce for sale certain foods that present a low risk of foodborne illness (e.g., honey, jams, home-made pasta, etc.). It requires that the selling of cottage foods only within the state of Florida and not across state boundaries and need to be properly packaged and labelled. It also needs to comply with all applicable county and municipal laws and ordinance regulating the preparation, processing, storage, and sale of cottage food products.

5.2.3. Sustainability Indices

The European Union (EU) SDG indicator set was first presented in 2017 by the European Commission addressing progress towards the 17 SDGs and was revised in 2021 report to consider EU policy and monitor the progress towards SD(217). Moreover, sustainable indices also aid in the quantification of sustainable urban development(266). Tradeoffs among social, environmental and economic sectors are expected with respect to those selected sustainability indices which varies over the sustainable development options(240). Yet the emphasis of sustainable development defers according to the interpretation of those sustainability indices(267). Therefore, transitions toward urban sustainability via multiple sectors presents a pathway instead of providing a direct evolution(268). A quantification of progression of sustainable development strategies with respect to various sustainability targets can be achieved from delineating sustainability indices to support decision-making with linkage to urban governance structure and function(239, 268). The selection of sustainability indices are dependent on the objectives or interest for sustainable development and can be pretty broad such as measurement of CO_2 emissions(268), natural capital index, ecological footprint index and welfare index(240). For instance, it is beneficial to use local sustainability indicators to address local-level governance and policy in the 29 local indicators presented by Tanguay et al.(267) which include crime rate, daily water consumption per person, unemployment rate, GHG emissions, and population density.

Since there are various aspects in sustainability, sustainability performance can be measured via sustainability indices in a similar approach that encompass environmental, social, and economic indicators tied with legal aspects. These indices also help explore and connect urbanization and the urban farming practices as summarized in **Table 19**. For example, carbon footprint can be linked to policy instruments aimed for carbon neutrality and GHG emission reduction while water footprint can be associated to the water conservation for climate change effects and the food consumption index can link population, local food production, and food security. For environmental sustainability, indices related to environmental impact such as carbon footprint (kg $CO_{2\text{-eq}}$), water footprint (L), and sea level rise are considered. In social sustainability, indices related to population density, food availability, and social equity such as the food consumption index (FCI), unemployment index (UI), and crime rate index (CRI) can be evaluated. Whilst in the economic sector, crop production index (CPI) is used to explore the economic sustainability with respect to income generated by crop produced at local scale, water reuse potential (WRP) relates the reduction of reclaimed water demand for irrigation by stormwater per farm area..

Table 19. Summary of Sustainability Indices

Sustainability	Index	Description
Environmental	Carbon footprint (CF)	Carbon footprint resulting from carbon emissions related to crop harvesting: • local crop production
	Water footprint (WF)	Water footprint resulting from water consumption related to: • local crop production
	Sea level rise (SL)	Climate change impact prediction of sea level rise according to SSP5-8.5 low confidence Nasa - IPCC AR6
Social	Food Consumption index (FCI)	Relation between food consumption and approximate population density near the urban farms
	Unemployment index (UI)	Standard values for the unemployment rate
	Crime rate index (CRI)	Standard values for crime rate
Economic	Crop production index (CPI)	Used to calculate the income generated from the crops produced in each urban farm utilizing Florida price (pf) and national crop price ($pf_{nat.}$)
	Water reuse potential (WRP)	Cost of water reuse potential is a ratio comparing the cost reclaimed water supply for irrigation after utilizing alternative water supply (e.g., stormwater) per UF area • Assuming stormwater storage of 20,000 L•yr^{-1}

1) Environmental Sustainability

The analysis on environmental sustainability focuses on the analysis of water footprint and carbon footprint from the production and consumption of resources in the urban farms and the activities of the people and entities. The carbon footprint related to the GHG emissions will be associated with production activities in the urban farms system described in Eq. (29)32. Similarly, the water footprint quantities water consumption from crop production activities is described in Eq . (30).

$$CF = \ area_{crop} \ * yield_{crop} \ * CEF_{area\ of\ crop} \tag{29}$$

$$WF = area_{crop} \ * yield_{crop} \ * WCF_{area\ of\ crop} \tag{30}$$

Where CF is the crop carbon footprint and contribution of carbon emissions (kg CO_2), $area_{crop}$ is the area for crop production (m^2), $yield_{crop}$ $is\ the$ maximum annual crop yield ($kg{\cdot}m^{-2}$), $CEF_{area\ of\ crop}$ is the carbon emission factor for each crop (kg $CO_2{\cdot}kg^{-1}$). Likewise, WF is the total water footprint and water consumption (L), and $WCF_{area\ of\ crop}$ is the water consumption factor for each crop (kg $CO_2{\cdot}kg^{-1}$).

Additionally, the analysis of sea level (SL) rise was performed according to the projections acquired from the IPCC AR6 report according to scenario SSP5-8.5 (Low Confidence) that accounts for possible climate change to having very high GHG and CO_2 emissions from climate change impact[(269)], with the projection for total sea level rise of 0.15 m by 2030 obtained from NASA sea level projection tool utilizing the IPCC AR6 report[(270)].

2) Social Sustainability

Social sustainability indices include the sub-indicators like supply chain, location, social innovations, training and education, health and safety, and so on[271]. Social sustainability is a relation between stakeholder (agents) and social development. Further, quality of life, governance, diversity, equality, food security, and social equity are also other indices analyzed and recently accepted in describing sustainable development[272, 273]. In our case, specific aspects of social sustainability like unemployment rate, crime rate, and food security in the context of food availability were examined. Crime rate and low income affect urban farming sites and therefore can help determine which urban farming location needs to receive priority leading to lower down the crime rate via urban farming activities. Food security is determined according to the USDA definition where 1 km^2 distance is selected for measurement of food access. The low access is defined when at least 33% of the population or 500 people live more than 1.6 km (1 mile) from supermarket or grocery store in urban regions. However, to describe food availability via the food consumption index (*FCI*), the average daily dietary food uptake for an adult of 4 kg[96] was used to determine the food demand according to the relation between food consumption and approximate population density near the UFs. The theoretical population near the UFs was determined based on the previous definition of low access region (from USDA) and the population density (cap•km^{-2}) obtained from postal zip code corresponding to each farm[274]. Considering that 33% of the population in this low access regions surround the UFs, the theoretical population near each UF is obtained by accounting for the population density that can be sustained by the farm area and factoring the 33% as the population to be fed by each UF. Thus, the *FCI* is obtained from the ratio between the average daily food consumption (fc_{UFA_i}) and food production (fp_{UFA_i}) as described in Eq. (31). If *FCI*>1 it represents a greater food demand over food supply).

$$FCI = \frac{fc_{UFA_i}}{fp_{UFA_i}} \qquad (31)$$

The unemployment index (UI) and crime rate index (CRI) were collected from the United States Census Bureau from the 2019 American Community Survey 5-year estimate[(275)], and the crime map using data from a leading data provider - ATTOM Data Solutions[(276)].

3) Economic Sustainability

Economic sustainability can integrate the elements that stimulate economic growth in sectors such as food, energy, and water sectors. These in turn should be capable of supporting the specific system (e.g., community or population). For example, cost analysis for local food production and food consumption in relation to energy supply via utility grid and/or microgrid can provide an idea of economic sustainability. Similarly, comparison of reclaimed water and stormwater consumption and cost of water utilization can further provide insight to economic sustainability.

Crop production income (CPI) index is used to calculate the income generated from the crops produced in each UF (fp_{UFA_i}) utilizing Florida price (pf) and national crop price ($pf_{nat.}$) obtained from USDA. For simplicity in comparison across the UFs, 15 crops (i.e., snap bean, cabbage, corn, cucumber, pepper, tomato, eggplant, squash, potato, lettuce, spinach, onion, okra, and radish) generally produced by the UFs are presumed to be cultivated throughout the farms, although not all are cultivated through the 23 UFs (**Table B2**). Assuming that equal quantities of each crop are cultivated at each farm (based on area), the estimated income can be derived based on the Florida fresh market price (Eq. (32)).

$$CPI = \sum_{i=23} fp_{UFA_i} * pf \qquad (32)$$

The water reuse potential (WRP) index is a ratio comparing the cost saving from of alternative water supply (e.g., stormwater) utilization and cost of reclaimed water supply per UF area (Eq. (33)).

$$WRP = \frac{WS - SWS * AW_{cost}}{RW_{cost}} \tag{33}$$

where WS is the water supply ($m^3 \cdot yr^{-1}$), SWS is the stormwater supply ($m^3 \cdot yr^{-1}$), rW_{cost} is the cost of reclaimed water supply ($\$ \cdot m^{-3}$), and UF_{area} is the area of an UF (m^3).

5.2.4. Urban Farm Clustering

Many urban spatial patterns have been evolving into more polycentric than centralized patterns(277). Most metropolitan cities can be described as polycentric urban regions characterized as polycentric urban networks(278). While clustering methods decrease the dissimilarities between the observations assigned to each cluster such effort can conform an emerging UFN. Thus, the clustering analysis approach aims to agglomerate the UFs in a UFN for exploring of priority of the UF growth. Within this context, the sustainability assessment of the UFs in the farming network must consider the intersections among social, economic, and environmental sustainability and its implications of being equity, bearable and viable (**Figure 22a**), since all three pillars of sustainability should be addressed to attain a "truly" sustainable development(279). In this philosophy, three sectors of food, energy and water are also highlighted in governance via policy for distribution and services for the public (**Figure 22b**).

Geo-clustering has been presented in various clustering approaches like k-means clustering, hierarchical clustering, and density-based spatial clustering. For example, three-dimensional feature space iterative clustering method with noise control was applied for image clustering by Guo and Haigh (280) in a 3D feature space. But gray clustering analysis was used by Wu et al.(281)

for classification of multiple elements and objects in a system that may have uncertainty and fuzzy factors. Further, fuzzy classification was used to classify the feature vector of vehicle feature space[(282)] and processing 3D brain magnetic resonance images[(283)]. Optimal clustering in high-dimensional spaces has been applied for data that may have high noise in grid clustering[(284)], and high-dimensional clustering of single-cell data of antibody panels[(285)]. In this study, we employ K-means clustering algorithms to analyze clusters based on high dimensional data embedded in different UFNs, projecting more than 10 indices in a 3D feature space with respect to social, environmental, and economic sustainability patterns. Variation in the specification of number of clusters in the K-means clustering analysis helps assess how the UFs can be grouped with varying level of sustainability.

The K-means clustering algorithm can form grouping based on assigning data points to a centroid with respect to Euclidean distance between the centroid and the data point locations. It can be manipulated in an iterative process that averages the points in the cluster and adjust the centroid to the updated location[(286)]. In a 3D space, the Euclidean distance (*d*) is determined from point A=(x_1, y_1, z_1) and B=(x_2, y_2, z_2) as described by Eq. (34).

$$d\,(A, B) = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2 + (z_1 - z_2)^2} \qquad (\ 34)$$

Mathematically, the aim of K-means is to minimize the sum of squared errors (SSE) within Euclidian distance. Further, K-means algorithm clusters data without given classification categories. In this optimization process (Eq. (35)), the objective function *f* is to minimize the sum of the squared Euclidean distance of each point to the nearest centroid as specified in Eq. (35) where *k* represents specified number *j* clusters (*j*=6, 8, 10, and 12), *m* is number of features for sample data *i,* X= (x_1,…, x_n) are set of data points, c=(c_1,.., c_j) represents a cluster set and c_j is a centroid of cluster *j*. To implement the K-means algorithm the number of iterations required for convergence was explored and the maximum number of iterations per run was specified as five iterations based on our results.

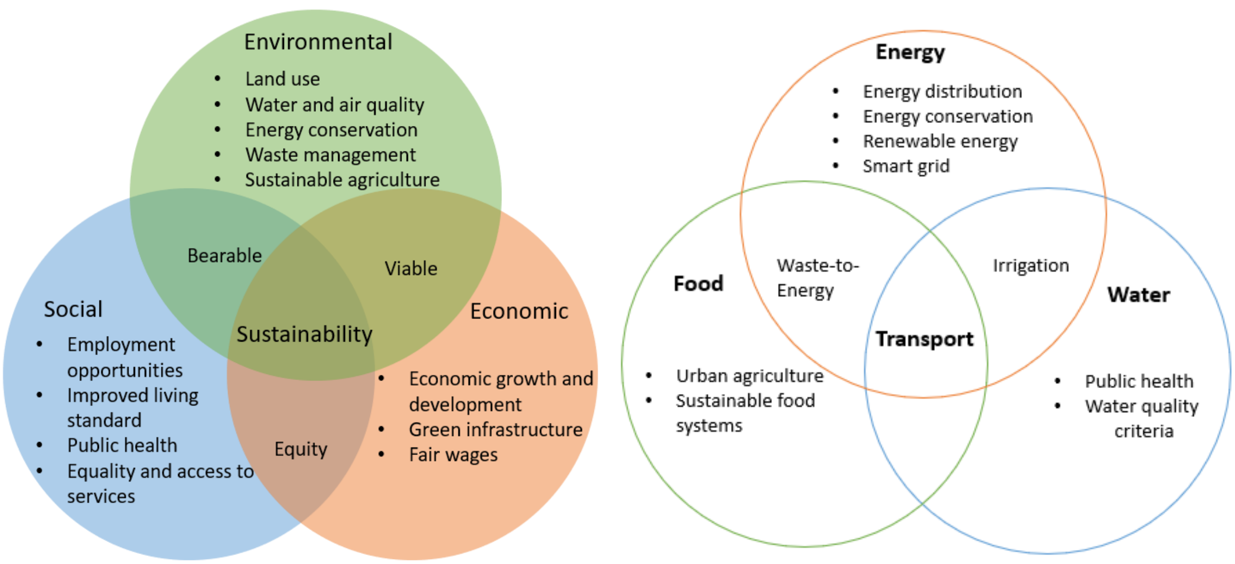
$$f = min \sum_{j=k}^{k} \sum_{i=1}^{m} \left\| x_i - c_j \right\|^2 \qquad (35)$$

The clustering strategies are formulated with respect to ten criteria that are implicated in the determination of the priority index (PI): 1) sustainability (social, economic, and environmental), 2) governance (agriculture funding for UFs), and 3) geographical location (proximity to food desert. Each criterion has unique attributes identified as A_1= crime rate index (CRI), A_2= unemployment rate index(UI), A_3= food consumption index (FCI), A_4= crop production income (CPI), A_5= water reuse potential, (WRP), A_6=carbon footprint (CF), A_7= water footprint (WF) and A_8= effect of sea level rise by 2030 according to IPCC AR6 SSP5-0.6 (If a UF impacted by sea level rise assign value of 1, otherwise 0), echoing the three pillars of sustainability (**Figure 22**). Attributes identified in governance are A_9= government funding (referred as GF) for food distribution (If non-profit or public, assign value of 1, otherwise 0). It was noted that the majority of the UFs (labeled as community gardens) are non-profit organizations or managed by public entities (e.g., town or city). A_{10}= proximity to food desert (FD) (If situated near food desert designated are assign value of 1, otherwise 0).

However, before implementation the K-means algorithm scaling and normalizing these attributes is performed where the 12 attributes of the data set were first standardized according to Eq. (36). Here n_{ik}= standardized sustainability index for attribute k of UF i, X_{ik}= attribute value for sustainability index k, $\overline{X}_{ik}$ is the mean attribute value and s_i is the standard deviation of i. This was done by using Scikit Learn's StandardScalar package. The standardization is important to avoid possible bias when assigning weights related to the importance of each attribute, since the values for the attributes are scattered over different ranges.

$$n_{ik} = \frac{x_{ik} - \overline{X}_i}{s_i} \qquad (36)$$

Since proximity plays a vital role in many aspects of an urbanization process the competitiveness in economic activities are site-specific in some cases(278). The geospatial data of the UFs (latitude and longitude) were thus transformed to cartesian coordinates by applying a 100 x 100 grid matrix that overlays in the ArcGIS map for plotting in a 3D space later in the clustering analysis.



(a) (b)

Figure 23. (a) Three Pillars of Sustainability (b) Governance and Policy Analysis

5.2.4.1. Optimization of UF System from Multi-Criteria Decision Making

To evaluate the implementation of clustering analysis and prioritization of the UF clusters, the various intrinsic criteria/attributes can be ranked in order of importance. For example, in multi-criteria decision making (MCDM), Technique for Order Preference by Similarity to the Ideal Solution (TOPSIS)(287) can be employed to generate weights for each sustainability index to echo the important factor given the individual cluster condition. Thus, a decision-making problem can be solved after conducting and evaluating the clustering strategies for the specified attributes. However, this MCDM process can be implicitly implemented directly to the clustering approach where the desired weights are assigned to the sustainability indices before application of clustering algorithm to assess the alternative scenarios (e.g., values and assumptions) in shaping the outcome of complex decision-making. Hence, to couple all the aspects of sustainability, the sustainability weight index is determined as follows for the sustainability indices for social, environmental, and economic sustainability. Given the different scenarios, the assignment of criteria weights reflects the importance of the criteria in the decision making[288].

$$w_{kj} = m_j n_{ki} \qquad (37)$$

where w_{kj}= weighted standardized vector for attribute/criteria j for UFs $i=\{1,\ldots, 23\}$, m_j = assigned importance of criterion {0, 1}, n_{ki}= standardized sustainability index for attribute j of UF. i. A common weighting method is the weighted score[289] based on the order of importance, and hence the values assigned for the weigthing factors range between 0-1 since the total score should be 1 (or 100%)[290]. The first scenario or equal sustainability scenario (S1) gives the same weighting factors to the social, economic, and environmental sustainability (i.e., m_j= 0.1 for each index). The second scenario or climate prioritization scenario (S2) accentuates the climate change impact (specifically carbon footprint, water footprint, sea level rise) therefore assigning m_j= 0.2 to CF, WF, and sea level rise and m_j= 0.0571 to each of the remaining indices. The third scenario or economic prosperity scenario (S3) highlights the economic gain (CPI) from local food production and possible cost saving from inclusion of stormwater by reducing reclaimed water demand for irrigation (WRP) thus also assigning m_j= 0.2 to CPI and WRP and m_j= 0.075 to each of the remaining indices.

The decision-making matrix is comprised of the summation across the ten criteria (*j= 1,.,., 10*) pertaining to sustainability (social, environmental, and economic sustainability indices), governance (agriculture funding for UFs), and location (proximity to food desert) (Eq. (38)). The direction from each attribute considers how precarious each UF site is summarized by using the Priority Index (PI). For instance, the UI, CI, FCI, CPI, WRP, CF, WF, SL, GF, and FD would all have a positive direction since it is desire to commence the scale-up process with UFs that are under more distressed conditions regarding food insecurity, societal problems, and environmental impacts.

$$PI = \sum_{k=1}^{n} w_{ij} \tag{38}$$

Lastly, to decide the priority of promoting these UF cluster in a UFN, the ranking is performed from the PI value where the highest PI signifies higher priority to the UFN to promote due to their precarious situation.

Further, the scenarios can be assessed to help stakeholders and decision makers understand which scenario needs greater attention for the implementation in a UFN. Using summations of the weighted vectors (w_{kj}) determined and normalized for the attribute/criterion derived for each scenario in the MCDM approach, the three scenarios can be ranked according to the PI score in which PI closer to 1 is preferred (291). First the weighted vectors are normalized (Eq. (39)) and then the scenario is selected for the highest calculated score P_i (Eq. (42)).

$$r_{ij} = \frac{w_{kj}}{\sqrt{\sum_{j=1}^{n} w_{kj}^2}} \tag{39}$$

$$S_i^+ = \left[\sum_{j=1}^{n}\left(w_{kj} - v_j^+\right)^2\right]^{1/2} \tag{40}$$

$$S_i^- = \left[\sum_{j=1}^{n}\left(w_{kj} - v_j^-\right)^2\right]^{1/2} \tag{41}$$

$$P_i = \frac{S_i^-}{S_i^+ + S_i^-} \tag{42}$$

where S_i^+= positive distance between alternative and overall score for alternative i, S_i^-= negative distance between alternative and overall score for alternative i. Here v_j^+= ideal best value based on w_{kj}, v_j^-= ideal worst value based on w_{kj}, and P_i= score of alternative *i*.

5.3. Results

5.3.1. Sustainability Assessment

The evaluation of sustainability indices was performed to try and undertake the three aspects of sustainability with the social, environmental and economic dimensions of the UFN system as mentioned by Mayer (239). Local indicators were used to evaluate and support local decision-making[(267)].The assessment of environmental sustainability provided insight to carbon emission and water consumption for each urban farm as well as possible impact from sea level rise based on projections for 2030. With carbon emission factors (kg $CO_{2\text{-eq}}$•m^{-2}) and water consumption factors (L•m^{-2}) for urban farming irrigation from literature (**Table B5**), the carbon footprint (CF) and water footprint (WF) were estimated for each UF site. It is noted that the estimated values of CF and WF were based on the inventory of dominant crops documented for production at each UF (**Table B5**); hence farms that grew more crops tended to have higher CF and CF (**Table 20**). Specifically, UF5, UF14 and UF16 obtained the highest carbon and water footprint related to crop production. After performing the sea level rise projection according to NASA-IPCC AR6 scenario SSP5-8.5 (low confidence), it was found that UF1, UF2 and UF3 located in Miami-Dade will be impacted with flooding according to a 300-meter delineation range (**Figure 23**). The same two UFs (i.e., UF2 and UF3) along with UF4, UF9, UF13-15, UF20 and UF23 showed large FCI indicating greater food demand in relation to food production (from farms). A suggestion to decrease the FCI and provide larger food supply in this area can be made possible by expanding the current cultivation area of the UFs. However, considering the possible impact of sea level rise in the future at UFs 1-3, it may be more feasible to incorporate a new UF at a location that may not be impacted by coastal flooding given projected climate change impact. This can call forth the need for additional policy instruments, incentives, and programs to aid in the sustainment of the UFs. Additional options can be evaluated to pinpoint some private and public entities that may develop more UFs with high sustainability level, such as UF15. Other important aspects in regard to social sustainability is the observed large unemployment rate and crime rate at UF4 relative to the other UFs., which is ~ 2.2 times higher than the 2021 national average unemployment rate of 5.3%[(292)]. However, the crime rate was slightly below the 2020 national crime rate of 387.8 (per 100,000 general population)[(293)]. Lastly, for economic sustainability, usually the UFs with larger agricultural land exhibited higher CPI such as UFs 14, 15, 16, and 23 related to its production potentials. The possible income from crop production is one important benefit to areas that suffer from economic inequity, hence this income can stimulate further urban agriculture in the UFN, thereby concurrently increasing its social sustainability. Yet, governance and policy have to be evaluated to determine if rectification is needed to enable the avenue for this transition in the UFN.

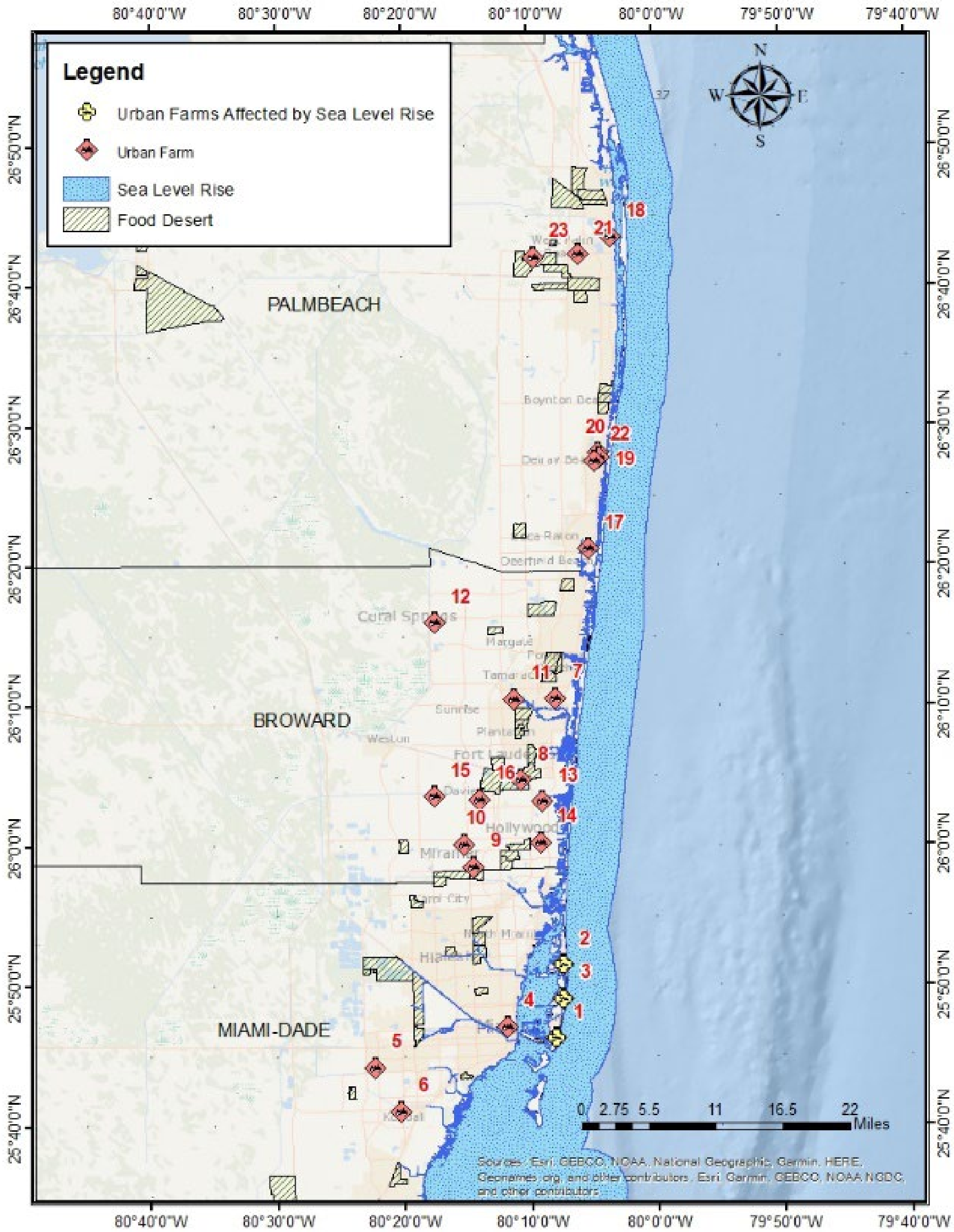


Figure 24. Location of UFs with respect with sea level rise for 2030 according to SSP5-8.5 low confidence Nasa -IPCC AR6

Table 20. Carbon and water footprint based on crop production for UFs

UF	Number of crops	Carbon footprint (kg $CO_{2\text{-}eq}$•yr^{-1})	Water Footprint (L•yr^{-1})
1	4	1.76×10^3	0.229×10^6
2	3	0.532×10^3	0.326×10^6
3	5	1.17×10^3	0.926×10^6
4	7	5.44×10^3	2.27×10^6
5	9	10.6×10^3	2.68×10^6
6	13	8.96×10^3	1.03×10^6
7	7	1.57×10^3	0.345×10^6
8	3	4.37×10^3	0.445×10^6
9	12	1.60×10^3	0.443×10^6
10	4	2.83×10^3	0.380×10^6
11	11	3.52×10^3	0.966×10^6
12	7	5.34×10^3	1.60×10^6
13	7	4.16×10^3	2.26×10^6
14	5	17.6×10^3	3.13×10^6
15	4	5.40×10^3	4.61×10^6
16	7	$31.4E \times 10^3$	8.61×10^6
17	2	0.287×10^3	0.136×10^6
18	4	0.357×10^3	0.296×10^6
19	12	2.28×10^3	0.633×10^6
20	12	2.72×10^3	0.703×10^6
21	9	5.63×10^3	1.39×10^6
22	11	6.29×10^3	1.73×10^6
23	12	$1.76E \times 10^3$	0.229×10^6

5.3.2. Clustering the Urban Farming Network

The clustering approach leads to generate the priority index (PI) which aggregates all the predefined indices into PI from a holistic view. The individual visualization of the social, environmental, and economic sustainability for each cluster can then help clarify the overall level of sustainability in a UFN (**Figure 24**). For instance, UF15 has greater food demand as demarcated by the larger FCI and the highest crime rate is presented at UF 4 (**Figure 24a**). While UF1, UF2, and UF3 are affected by sea level rise, UF16 has the highest CF and WF among all the UFs (**Figure 24b**). The UFs with proximity to food deserts include UF1-UF3, and UF 12 (**Figure 24c**). It is noticeable that most UFs are supported by government funding (except for 4 UFs).

Figure 25. Representation of standardized a) social, b) environmental and c) economic sustainability indices of UFs.

The analysis of the UFN can follow those clusters that maximize the sum of different sustainability level of the 23 UFs (**Figure 25**) which can be easily summarized by PI across three scenarios (**Table 21**). The three proposed scenarios in this study try to address the impact of varying aspects of sustainability for each UF. The equal sustainability scenario (S1) provides a base for comparison with similar importance placed in all the criteria for decision-making, whilst the climate prioritization scenario (S2) and economic prosperity scenario (S3) prioritize climate change impact and economic gain (CPI) from local food production, respectively. Comparison of both S1 and S2 yielded similar relationship for all k-clusters (6, 8, 10, 12) except for S3 via visual distinction according to the 3-dimensional feature space (**Figure 25**).

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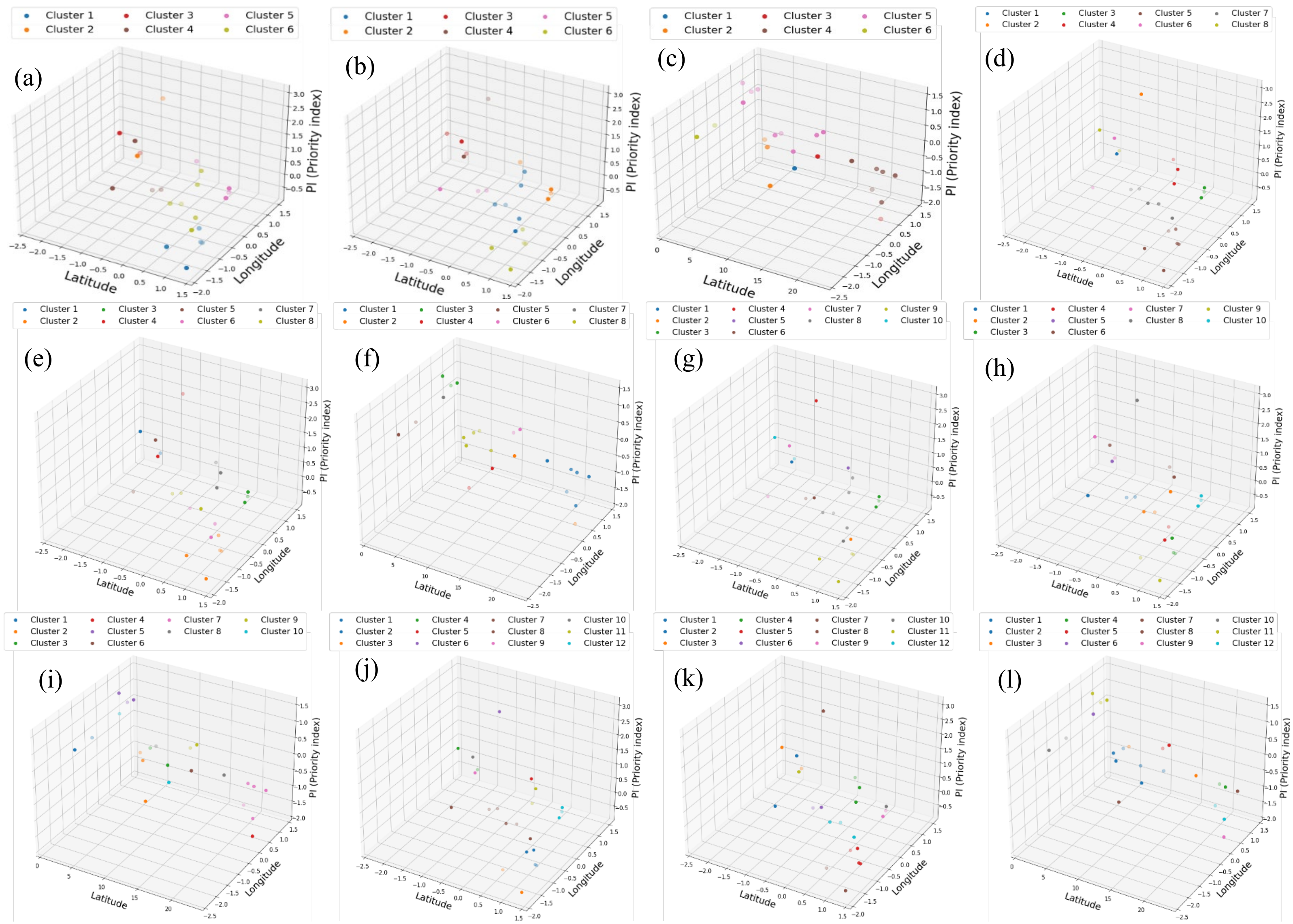


Figure 26. Visualization of clusters in 3D feature space for scenario 1, scenario 2, and scenario 3 for a), b),c) k=6, d), e), f) k=8, g), h), i) k=10, and j), k), l) k=12

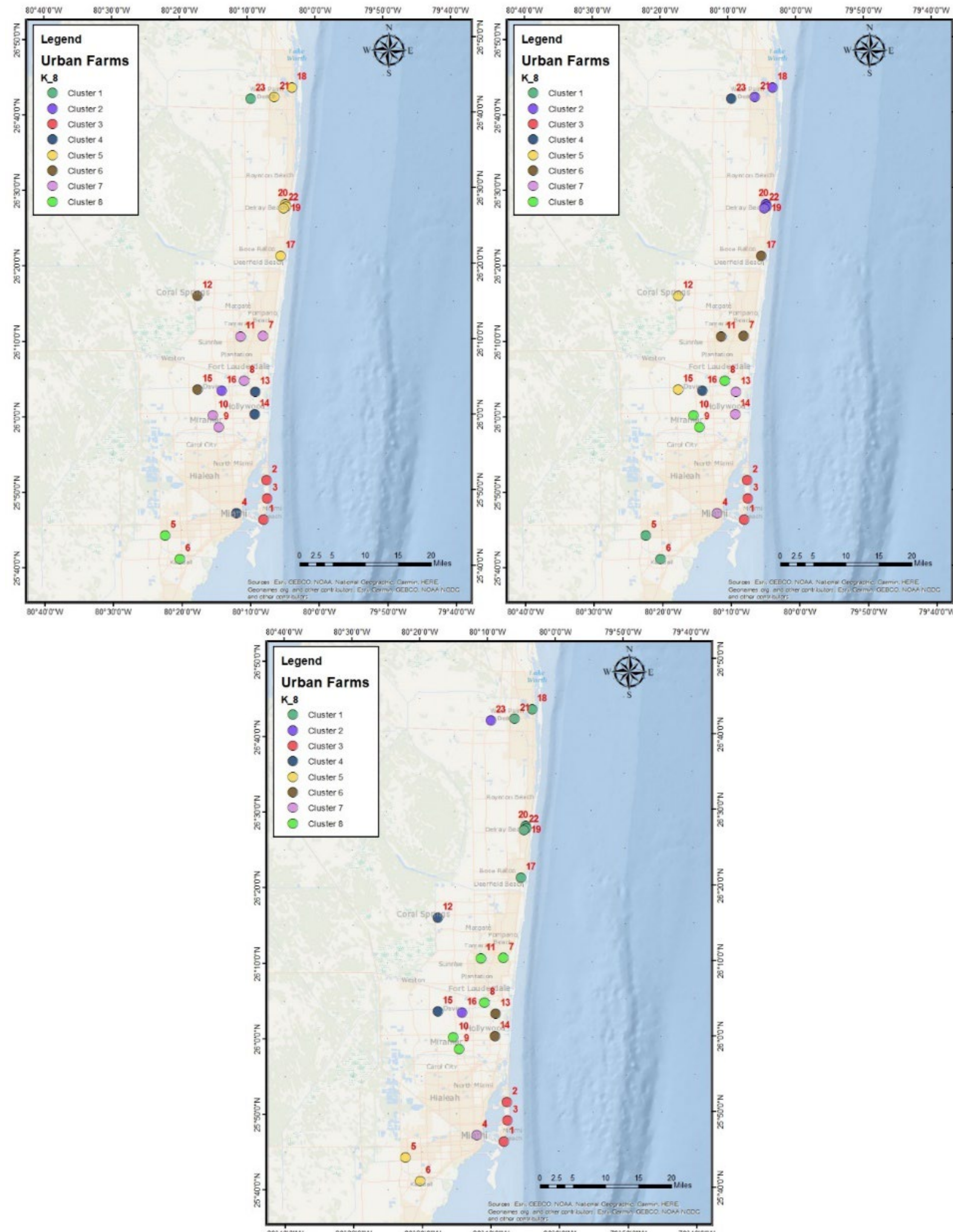
Table 21. Summary of clustering (k=8) of UFs for three scenarios

Scenario 1		**Scenario 2**		**Scenario 3**	
Cluster number	UF	Cluster number	UF	Cluster number	UF
1	23	1	5	1	17
2	16		6		18
3	1	2	18		19
	2		19		20
	3		20		21
4	4		21		22
	13		22	2	16
	14	3	1		23
5	17		2	3	1
	18		3		2
	19	4	16		3
	20		23	4	12
	21	5	12		15
	22		15	5	5
6	12	6	7		6

Scenario 1		Scenario 2		Scenario 3	
	15		11	6	13
7	7		17		14
	8	7	4	7	4
	9		13	8	7
	10		14		8
	11	8	8		9
8	5		9		10
	6		10		11

To further showcase the clustering results, the case of k= 8 clusters was selected for further assessment and visualization of the three scenarios as this clustering scheme in general has a distribution of at least 2 UFs for cluster (**Figure 26**). To accommodate sustainable urbanization, polycentric evolution in expansion and growth may be more appropriate for the UFN since polycentric urban development considers the shift of urban clusters followed by the reshaping of regions from population growth. The formation of subcenters has resulted in a polycentric urban pattern exhibited in the urban regions driven by urban spatial dynamics[(294)]. For instance, Yue et al. [(295)] presented the analysis of polycentric urban expansion in Hangzhou, China focused on development clustered around economic activities..

(a) (b)



(c)

Figure 27. Location of UFs in clusters k=8 a) scenario 1, b) scenario 2, c) scenario 3

5.3.3. Multicriteria Decision Making

The MCDM approach was performed from the calculated PI pertaining to urban farm priority to promote due to higher vulnerability in the UFN. For demonstration, the k-cluster= 8 was selected for final MCDM to rank the clusters from the most to the least vulnerable to determine the priority for the three scenarios (**Table 22**). In the equal sustainability scenario (S1), where equal importance was placed to the sustainability indices the integration of UF clusters from highest priority to the least transition from Cluster 2→Cluster1→ Cluster 4→ Cluster 6→ Cluster 5→ Cluster 8→ Cluster 7→ Cluster 3. In the climate prioritization scenario (S2) the UFs that have higher priority are Cluster 4 and Cluster 7 as opposed to S1 where Cluster 7 was one of the last ranked. While for the economic prosperity scenario (S3) with importance on economic gain from local food production and water reuse potential, both Cluster 2 and Cluster 4 were ranked with highest priority. Further, since the implementation of the UF network is reliant on stakeholder decision making, the scenarios can be ranked using TOPSIS to help identify which scenario scaling-up scenario show be followed for the implementation of the UFS in the clusters. As a result, S2 was ranked the highest followed by S3, and therefore it is suggested that the proposed UFN should follow S2. In this scenario, all sustainability indices are given higher priority due to climate change in the decision-making context.

Table 22. Ranking of UFs Priority Index (PI)

	Scenario 1	Scenario 2	Scenario 3
Rank	**Cluster number**	**Cluster number**	**Cluster number**
1	2	4	2
2	1	7	4
3	4	5	6
4	6	2	1
5	5	1	5
6	8	6	8
7	7	3	7
8	3	8	3

5.4. Discussion

Network science is comprised of analysis of networks in various disciplines such as information science, computer science, social network analysis, physics, and mathematics[(296)]. Multi-organizational governance can also be perceived as a form of network[(265)]. Thus, the governance structure is essential to the interaction of organizations, agents, and stakeholders in complex decision making. Polycentric governance system is an approach to have multiple independent governing entities[(297)] necessary for achieving collective sustainability. For instance, crime rate can be linked to social equity in a cyclic pattern given that key factors in influencing crime rates include education levels, racial and ethnic backgrounds. Further, crime rate can indirectly affect economic growth[(298)] which can be linked to income inequality and unemployment. Yet, this observation also applies to the v structure of renewable energy due to a variety of alternatives with respect to different technologies, which hinders the cost-effectiveness while transitioning to the next stage[299]. Therefore, governance structure has a key role through the implementation of relevant policies in the urban food-energy-water nexus as described in **Table 23**. This is intimately in association with water sources (e.g., groundwater, city water, stormwater, reclaimed water) and energy sources (e,g., utility grid and renewable energy).

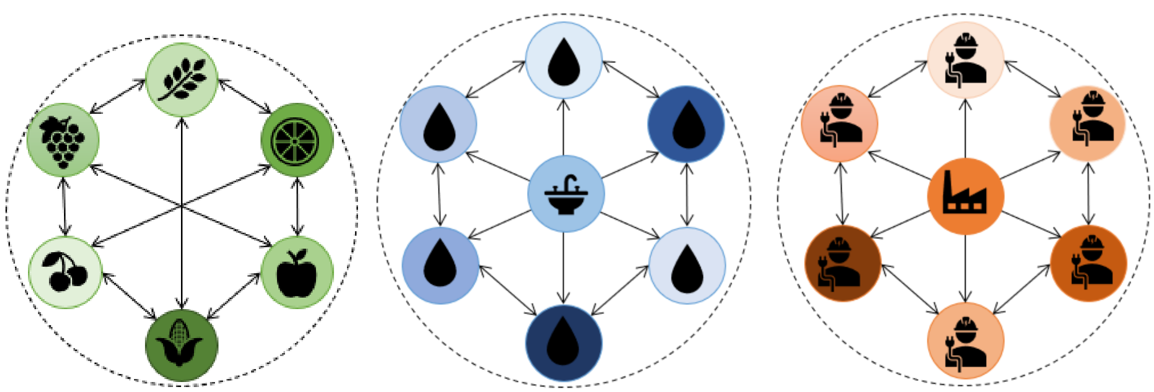
To help the UFN transition towards urban sustainability with an emphasis on planning via S2, the governance function entails the actions from governing authorities facing policies and incentives (e.g., local level) that promote social, economic, and environmental sustainability. Similarly, S1 can be described as a base scenario that does not need much effort via reshaping policies such as generation of new policy instruments. However, the results from S2 and S3 can suggest how decision-making, governance, policy, and planning of UFN aimed at sustainability are interrelated with a cascading effect.

Table 23. Subsidizes and grants (USDA)

Food	Description	Energy	Description
Florida Farm Subsidies	Subsidies specific to crops (peanut, sugar, cotton) include price loss coverage, market assistance, quota buyout, and agricultural risk coverage	Federal Solar Investment Tax Credit (ITC)	Promote renewable energy, specifically solar energy, providing a 26% tax credit for residential and commercial solar systems
Environmental quality incentives program (EQIP)	Provides financial assistance to agricultural producers to preserve surface water and groundwater sources, improve air and water quality, and reduce soil erosion	Solar System Property Tax Exemption	Property tax exemption on the additional home value from the solar system
		Home Solar System Sales Tax Exemption	Tax exemption for residential solar system installation

5.4.1. Governance of Urban Food Production and Distribution

A centralized food supply system takes care of the connection between multi-source food supply systems (food security and nutrition) and urban system as food security policies are driven by top-down and territorial approaches that can be fragmented with lacking coordination[300]. Further, multi-level architecture of food system is affected by territorial governance at different scale that can be also context-specific. Nevertheless, this implies a "one-size fits-all" approach is not representative of the majority of the urban areas. A decentralized governance structure that promotes urban agriculture according to consumer demand, localized sourcing, distribution, and procurement is preferred for sustainable urban development. Transitioning towards securing food supply as part of food sustainability and emergency response in this governance structure, a decentralized decision support is reflected as self-managed or self-governed network (**Figure 27a**) where a shared responsibility between different partners is desired. However, the current governance structure related to food supply is more closely described by a NAO structure where decisions and policy regarding food safety permitting, processing, and handling is primarily controlled entity outside of the network (e.g., FDA and USDA). Because of the food safety policies and regulations, it can be difficult for the UFN to transition to a self-governance mode given the advantage of the UFN is to enable the provision of local food source in dealing with regular food supply and emergency response such as COVID-19 impact or hurricane landfalls in coastal regions.



(a) (b) (c)

Figure 28. Network structures and functions in a Food-Energy-Water System (a) Urban food distribution network, (b) Water governance structure, (c) Energy distribution network

5.4.2. Governance of Sustainable Water Management

Water governance focuses on water utilization and management such as allocation, distribution and equitable use establishing legislations and water policies. Here we refer to water governance as the level of governance of water stakeholders for decision-making in the context of UF network although the case study is at a local scale that the “players” of the water governance encompass various organizations (i.e., regulatory authorities, community organizations) and individuals. Given the source of freshwater, the water supply system is mostly a centralized institutional system where decision-making is distributed among the players of the municipal authority (**Fig. 7b**) and managerial policies are enacted by local, state, and federal legislation via centralized governance. Policy instruments can also affect the supply chain of water for agriculture irrigation. With the current operations in south Florida, most urban growers use groundwater for irrigation, which is a “free” resource except for the initial cost for pump installations. Few operations use tap water or city water due to the high cost, and such practices are more applicable to productions systems like aero- or hydroponics that have higher standards of water quality and water chemistry but also possess high water use efficiency. Using reclaimed water (e.g., rainwater, stormwater) can have great potential towards sustainable practices. However, it is not widely adopted in the area, due to the lack of infrastructure for sizable operations in urban food production. It was observed in some urban growers that use rain barrels connecting to rooftops to supplement water needs for irrigation as well as the use of water from small urban ponds. Yet, the combination of stormwater reuse provides an additional layer to decrease the community vulnerability to water shortages, especial with the concerns of climate change and substantial drawdown of groundwater table. Stormwater reuse with other low impact developments can support urban farming irrigation and be further linked to climate change, as stormwater can be utilized as an alternative water supply to support farming in drought events. In this context, the governance structure is a hybrid of centralized and decentralized system (**Figure 27b**) that can be more reliable to the UFN as decentralized systems can have pros and cons relative to centralized systems (301). The implementation of decentralized water management that can reduce the dependency of the current centralized system such as decentralized wastewater treatment systems that are not connected to centralized sewer systems can reshape the governance structure. Thus, stormwater reuse can further support and decrease the water demand specifically for the UFs with the highest WF (e.g., UF16), which lead to increase their sustainability.

5.4.3. Governance of Energy Production and Distribution

Based on the characteristics of the energy sector which has fewer restriction and regulations in comparison to the food and water sectors sensitive to the health and welfare, it can be easier to manage policy wise. Unlike food and water which go directly to the consumer or the production process, energy is more of a service and intangible in comparison. Energy governance encompasses energy service and supply distribution; however the governance structure is very fragmented (302). The polycentric approach can better depict the governance infrastructure in energy sector (301). Based on the characteristics of the energy network and the UFN, a lead organization governance structure can be selected **Figure 27c**) as it is a more centralized approach that involves one major member (energy generating facility) to manage the network of power distribution. The electricity generated by centralized facility is distributed through the electric power grid to multiple end-users like the UFs. With the potential inclusion of local microgrid, energy storage units, and renewable energy production technologies which can operate as decentralized energy sources, the UFN can have a hybrid energy supply system between centralized and decentralized operation modes. Further, there are also governance structures to persuade sustainability and energy security. This type of decentralized energy source can not only provide a better energy reliability to the UFN but decrease the CF associated with energy from fossil fuels, hence enabling the UFs to transition to be more supportive for UFNs in the future.

5.5. Final Remarks

In this study, the evaluation of sustainability patterns via a suite of environmental, social, and economic indices provided a means to quantify the priority of each UF and help policy makers to foster a better governance program for these UFs with priority. According to SSP5-8.5 low confidence NASA -IPCC AR6 projections of 2030 for sea level rise, it was found that UF 1, UF 2, and UF 3 will be impacted with flooding according to a 300-meter delineation range. Given current understanding in governance and policy, MCDM assessment was incorporated into the clustering analysis to help visualize the clustering structures of the UFN and rank them in accordance with greater need for improvement or level of social vulnerability. In scenario 1, where equal importance was emphasized in these sustainability indices the ranking of UF clusters from the highest priority to the lowest ones for transition is: Cluster 2→Cluster1→ Cluster 4→ Cluster 6→ Cluster 5→ Cluster 8→ Cluster 7→ Cluster 3. In general, UF 2 and UF 4 were ranked the highest across the three decision making scenarios; however, other variables (e.g., that dive further into the social-economic aspect) can be assessed to explore what differentiates these UFs from the rest in the UFN. This may require a more substantive approach to better understand the current demographics at the regions where the UFs are located as well as the urban agriculture strategies employed at each farm. We anticipate that our approach can be used to manage any high-dimensional UFN in different urban environments. Future work can be expanded to encompass evaluation of the decision-making process for UFs in the Miami metropolitan area using innovative technology hubs to promote urban agriculture in an urban food-energy-water nexus.

CHAPTER 6: CONCLUSION

Since various forms of nexus research such as FEW or FEWW nexus implementation have been extensively investigated, there is a need to transition into exploring future innovative aspects for greater sustainability while considering climate change and policy instruments. For instance, we may focus on interdisciplinary solutions of reclaimed wastewater and stormwater treatment that provide co-benefit while also decreasing the community vulnerability due to energy scarcity. This is important to reduce energy consumption and increase efficiency in reclamation facilities as these facilities are one of the major consumption sources of energy in a municipality consuming 30-40% of total energy[(303)]. Finding a technology alternative for the cost-effective treatment of stormwater can facilitate the decrease of reclaimed wastewater utilization. Although rainwater collected directly, unless affected by stormwater runoff from rooftops, is expected to be uncontaminated while stormwater can be treated via electrolysis and fuel cell for hydrogen generation stored in a hydrogen storage system as described by Zhang et al.[(64)]. However, disadvantages can arise from the use of stormwater (rainwater) harvesting devices in urban agriculture due to maintenance fees to control eutrophication impact (e.g., algae growth) with storage limits.

The first 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.

Since considerable amount of energy is consumed by the construction and building industry, and the energy sector contributes substantially to global greenhouse gas (GHG) emissions. Supporting the United Nations agenda for net-zero emissions and decarbonization, the retrofit of existing buildings can provide huge opportunity to reduce its energy consumption and subsequent GHG emissions. As buildings are the central part of energy demand in the urban regions, it is thus vital to explore the decarbonization pathways that enhance energy efficiency in an urban food-energy-water-waste (FEWW) nexus. Hence, this study aimed to establish a community-scale FEWW nexus leading to highlight decarbonization pathways with a simulation analysis for the Baptist Hospital Medical Arts Building in Miami, Florida. Several potential retrofit alternatives were proposed for analyzing building energy consumption, energy requirements for roof-top or green-house crop production, and potential energy savings from renewable energy harvesting in a FEWW nexus. For all proposed scenarios, an integrated modeling framework was designed to account for: 1) building energy consumption via the EnergyPlus, 2) waste management and water utilization via a system dynamic modeling, and 3) GHG emissions by life cycle assessment to facilitate decision-making. It is indicative that the suggested retrofit solutions with respect to the nexus approach can substantially reduce the community-scale energy demand. For instance, the incorporation of solar photovoltaic (PV) systems (i.e., rooftop, parking lot, parking garage and floating solar PV) sustained approximately 72% of net energy demand (Scenario A3), while the integration of all solar, wind and anaerobic digestion alternatives provided around 41% of net energy demand (Scenario A6). In scenarios A5 or A6, it is beneficial for avoiding energy consumption from the utility grid and more than 250% of GHG emissions are the mostly preferred in the decarbonization pathways due to the use of renewable energy by 2030.

Moreover, urban areas often face versatile stressors (e.g., food security, congestion, energy shortage, water pollution, water scarcity, waste management, and storm and flooding), requiring better resilient and sustainable infrastructure systems. A system dynamics model (SDM) explored for the urban region of Orlando, Florida, acts as a multiagent model for portraying material and energy flows across the food, energy, water, and waste (FEWW) sectors to account for urban sustainability transitions. The interlinkages between the FEWW sectors in the SDM are formulated with multiple layers of dependencies and interconnections of the available resources and their external climatic, environmental, and socioeconomic drivers through four case studies (scenarios). The vital components in the integrated FEWW infrastructure system include urban agriculture associated with the East End Market Urban Farm; energy from the fuel-diverse Curtis H. Stanton Energy Center; reclaimed wastewater treated by the Eastern Water Reclamation Facility, the Water

Conserv II Water Reclamation Facility, and stormwater reuse; and solid waste management and biogas generation from the Orange County Landfill. The four scenarios evaluated climate change impacts, policy instruments, and land use teleconnection for waste management in the FEWW nexus, demonstrating regional synergies among these components. The use of multicriteria decision-making coupled with cost-benefit-risk tradeoff analysis supported the selection of case 4 as the most appropriate option as it provided greater renewable energy production and stormwater reuse. The SDM graphic user interface aids in the visualization of the dynamics of the FEWW nexus framework, demonstrating the specific role of renewable energy harvesting for sustainably transitioning Orlando into a circular economy.

Environmental, social, and economic sustainability patterns interact in various dimensions of urban environment. Exacerbated population growth triggers the emphasis on better resource management strategies addressing the balance of supply and demand over food, energy, water sectors while considering social and economic development. Promoting sustainable development goals requires governance structures and functions within the food, energy, and water sectors, specifically due to the polycentric urban development. Therefore, the last study places an emphasis of food security via an urban farming (UF) network in the greater Miami metropolitan area encompassing three counties (Palm-Beach, Broward, and Miami-Dade). A suite of sustainability indices were quantified for clustering analysis to agglomerate the UFs and help identify the priority of clusters in terms of vulnerability or risk level according to their priority index in multicriteria decision making. The case of 8 clusters was selected for visualization of the UFs ranked by multicriteria decision making based on scenarios prioritized for governance under the impact of climate change, social equity, and economic development. The role of governance structure was highlighted finally for signifying the incentive programs to enhance the overall sustainability performance of UFs in an urban food-energy-water nexus.

APPENDIX A: BUILDING ENERGY RETROFIT STRATEGIES AND DECARBONIZATION PATHWAYS IN COMMUNITY-SCALE FOOD-ENERGY-WATER-WASTE NEXUS

Table A1. EnergyPlus Green Roof Model (EcoRoof) Input

Parameter	**Input**
Height of plants	0.3 m
Leaf area index	5
Leaf reflectivity	0.2
Leaf emissivity	0.95
Minimum stomata resistance	180
Soil layer name	EcoRoofSoil
Roughness	MediumSmooth
Thickness	0.18 m
Conductivity of dry soil	0.4 W/m-K
Density of dry soil	641 kg/m^3
Specific heat of dry soil	1100 J/kg-K
Thermal absorptance	0.95
Solar absorptance	0.80
Visible absorptance	0.70
Saturation volumetric moisture content of the soil layer	0.4
Residual volumetric moisture content of the soil layer	0.01
Initial volumetric moisture content of the soil layer	0.20
Moisture diffusion calculation method	Advanced

Table A2. Summary of VAWT EnergyPlus Input Parameters

Parameter	Input
Number of turbines	3
Rotor type	vertical
Power Control	variable speed fixed pitch
Rated rotor speed(rev/min)	100
Rotor diameter (m)	5.2
Overall height (m)	11
Number of blades	3
Rated power (kW)	10
Rated wind speed (m/s)	11
Cut in wind speed (m/s)	3
Cut out wind speed (m/s)	25
Fraction system efficiency	0.75
Maximum tip speed ration	5
Blade cord area	2.08 m^2
Blade drag coefficient	0.9
Blade life coefficient	0.05

Table A3: Summary of input and output parameters for anaerobic digester

Parameter	Value	Note
Anaerobic capacity	0.605 ML (0.16 MGD)	Biogas tank capacity: 1.2-1.6 m^3/person [a]
Effective Operating Capacity	98%	Suggested by EPA spreadsheet
Percent of total volume remain as buffer capacity	4%	Suggested by EPA spreadsheet
Max capacity of digester	0.567 ML (0.150 MGD)	Calculated from EPA spreadsheet
Digester type	Thermophilic	[a]
Operating Temperature	40ºC (104 ºF)	Assumption (Optimum)
VS% reduction	30%	Suggested by EPA spreadsheet
Annual O&M costs	$2,500/yr	Suggested by EPA spreadsheet
Biogas production rate	0.94 m^3 biogas/kgVS destroyed (15 ft^3 biogas/lb VS destroyed)	Suggested by EPA spreadsheet Range 12-18 (Metcalf and Eddy)
Feedstock	Food waste (i.e., garden waste) and wastewater from building	
Feedstock quantity/ Capacity	8.44 kg/day (0.00923 short tons/day)	Assumption based on SDM (3,059 kg/yr)

Parameter	Value	Note
Solids content	2%	Range 5-10% [c]
Composite solids fed to digester (%TS)	5%	Range 4-10%
HRT	15 days	Suggested by EPA spreadsheet Typical for thermophilic is 10-16 days
Percent biosolids	16%	Suggested by EPA spreadsheet
Temperature of unheated feedstock	15.16°C (60 °F)	Suggested by EPA spreadsheet
Biogas Use	Combined heat and power (turbines)	Biogas heats digester
	Results	
Biogas generation per digester	12.88 kg/yr (455 ft^3/yr)	Calculated from EPA spreadsheet
Total methane generation	7.73 m^3/yr (273 ft^3/yr)	Assuming 0.6 Methane/Biogas ratio or 60% methane content in biogas
Biogas value	$2.70	EPA spreadsheet
High heat value of methane	37,651.16 KJ/m^3 (1,011 BTU/ft^3)	Conversion EPA
Heat value estimate	0.218 MJ/yr (0.207 MTU/yr)	Calculated from EPA spreadsheet

Parameter	Value	Note
kWh of methane	23 kWh/yr	Calculated from EPA spreadsheet
	82,799.96 KJ/yr (78,479.22 BTU/yr)	Conversion 1 kWh= 3412.14 BTU
Available capacity	37,982.82 L/day (10,034 gal/day)	Calculated from EPA spreadsheet
Average annual initial feedstock heating	46,768.9 MJ/yr (44,302 MBTU/yr)	Calculated from EPA spreadsheet
Total energy needed for heating	47,746.15 MJ/yr (45,257 MBTU/yr)	Calculated from EPA spreadsheet
Average energy loss	1,007.5 MJ/yr (955 MBTU/yr)	Calculated from EPA spreadsheet
Heat value estimate	291,060.8 KJ/yr (275,887 BTU/yr)	Calculated from EPA spreadsheet

[a] (SSWM[304])

Table A4. Crop yield, water, and electricity consumption for SDM input

Location	Cultivation condition	Yield (kg/m^2.y)	Electricity (kWh/kg)	Water Depletion (L/kg)	Carbon Emissions (kg $CO_{2\text{-}eq}$/kWh)	Reference
			Tomato			
Boston, USA	Green roof	16.3	0.920	68.10	2.1	Goldstein, et al.[85]
Bologna, Italy	Green roof	13-14	0.317	88.1	0.0679	Sanyé-Mengual et al.[305]
			Cabbage			
	Open field		2.91	280	0.12	HEALable [306]
Uppsala, Sweden	Green roof	0.3				Roy[307]
Seoul, Korea	Open field	5.54			0.57ⱡ	Lee et al.[308] ⱡClune, et al.[309]

*Energy required for crop production (e.g., irrigation)   [a] average value

Table A5. Carbon Emission Factors for Carbon Footprint Calculation

Parameter	GHG Emissions	Reference
PV (mono-si)	47.9 g $CO_{2\text{-eq}}$/kWh (30-year life)	
VAWT (5 kW capacity)	55 g $CO_{2\text{-eq}}$/kWh (20-year life)	Kouloumpis et al.[310]
Utility Grid[ⱡ]	0.378	Nugent and Sovacool[311], EPA[183]

[ⱡ]Corresponds to EPA eGrid subregion FRCC (converted from lb $CO_{2\text{-eq}}$ /MWh to kg $CO_{2\text{-eq}}$ / kwh)

Table A6. Water Consumption Variables for Water Footprint Calculation

Parameter	Water Consumption	Reference
PV[a]	2.16×10^{-5}~1.09×10^{-4} m^3/kWh	Mekonnen et al.[312]
Wind[a]	7.20×10^{-7}~4.32×10^{-5} m^3/kWh	Mekonnen et al.[312]
Utility Grid[ⱡ]	2.88×10^{-4}~7.56×10^{-3} m^3/kWh	Macknick et al.[313] Mekonnen et al.[312]

[a] Water consumption related to power generation, distribution, and operation and maintenance (O&M)
[ⱡ] Assuming primary fuel type is coal with generic cooling tower converted from gal/MWh to m^3/kWh)

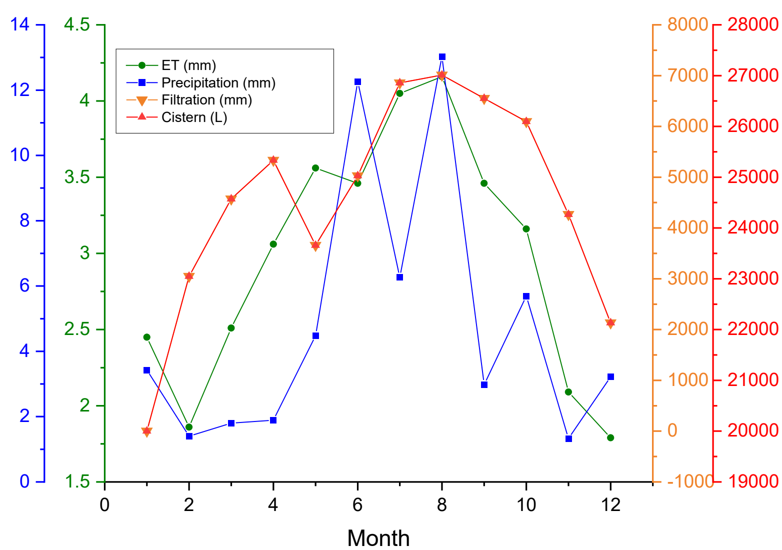


Fig. 1A. Overall relationship among evapotranspiration, filtration, and water input/output in the rooftop farming activity

APPENDIX B: INTEGRATING SUSTAINABILITY PATTERNS AND GOVERNANCE STRUCTURES VIA CLUSTERING ANALYSIS AND MULTICRITERIA DECISION MAKING FOR URBAN FARMING NETWORK

Table. B1. Summary of Urban Farm Sites and Geographic Location (UFs)

UF ID	Name	Area (m^2)	County	Address	Longitude	Latitude
1	Joseph Villari Victory Garden	323.04	Miami-Dade	226 Collins Ave. Miami Beach, FL 33139	-80.134	25.772
2	North Beach Community Garden	638.70	Miami-Dade	7398-7342, Dickens Ave, Miami Beach, FL 33141	-80.125	25.859
3	Pine Tree Park Community Garden	823.17	Miami-Dade	4401 Pine Tree Drive Miami Beach, FL 33140	-80.125	25.818
4	The Green Haven Project	2124.30	Miami-Dade	1160 NW 2nd Ave, Miami, FL 33136	-80.199	25.786
5	St. Simon's Farm	2337.17	Miami-Dade	10950 SW 34th St, Miami, FL 33165	-80.373	25.737
6	Baptist Hospital	3311.94	Miami-Dade	8900 N Kendall Dr, Miami, FL 33176	-80.339	25.686
7	Urban Farming Institute	358.95	Broward	1101 NE 40th Ct, Oakland Park, FL 33334	-80.133	26.177
8	Harpke Family Farms	426.81	Broward	2781 SW 36th St, Davie, FL 33312	-80.178	26.078
9	Miramar Community Garden	430.54	Broward	3700 Largo Dr, Miramar, FL 33023	-80.242	25.976

UF ID	Name	Area (m^2)	County	Address	Longitude	Latitude
10	Pembroke Pines Community Garden	519.81	Broward	8500 E Cypress Dr, Pembroke Pines, FL 33025	-80.255	26.002
11	Lauderdale Lakes Community Garden	888.32	Broward	4200 NW 36 ST. Lauderdale Lakes, FL 33319	-80.188	26.176
12	Rotary community garden of coral springs	1281.85	Broward	2915 Sportsplex Drive Coral Springs, FL 33065	-80.292	26.267
13	Dania Beach Patch Community Garden	2389.80	Broward	1200 NW 1st St, Dania Beach, FL 33004	-80.156	26.053
14	Highland Community Garden	3911.07	Broward	2702 Funston St, Hollywood, FL 33020	-80.154	26.005
15	Tree Amigos	5057.91	Broward	10900 SW 48th St, Davie, FL 33328	-80.293	26.06
16	Marando Farms and Ranch	8067.86	Broward	5151 SW 64th Ave, Davie, FL 33314	-80.234	26.056
17	Boca Raton Community Garden	345.85	Palm-beach	NW 4th St, Boca Raton, FL 33432	-80.088	26.355
18	Henrietta Bridge Farm	440.63	Palm-beach	1400 Henrietta Avenue West Palm Beach FL 33401-2531	-80.057	26.726
19	Swinton Community Garden	615.03	Palm-beach	Swinton & Atlantic Ave 33444 Delray Beach, FL, 33444	-80.073	26.463

UF ID	Name	Area (m^2)	County	Address	Longitude	Latitude
20	Cason Community Garden	817.37	Palm-beach	342 North Swinton Avenue; Delray Beach, FL 33444	-80.075	26.468
21	Westgate Community Farm	1244.71	Palm-beach	1130 Wabasso Dr, West Palm Beach, FL 33409	-80.1	26.705
22	Southwest Community Garden	1590.46	Palm-beach	119 SW 7th Avenue; Delray Beach, FL 33444	-80.08	26.459
23	Nicoya Farm	8040.60	Palm-beach	1637 Skees Rd. West Palm Beach, FL 33411	-80.159	26.702

Table B2. Urban Farms (UFs) Crop information

UF ID	Name	Area (m^2)	Sweet corn	Snapbean	Bell pepper	Cucumber	Tomato	Cabbage	Okra	Eggplant	Summer squash	Potato	Lettuce	Spinach	Carrots	Onion	Radish	Total Number of
1	Joseph Villari Victory Garden	323.04				✓	✓						✓		✓			4
2	North Beach Community Garden	638.70					✓						✓		✓			3
3	Pine Tree Park Community Garden	823.17	✓	✓								✓				✓	✓	5

UF ID	Name	Area (m^2)	Sweet corn	Snapbean	Bell pepper	Cucumber	Tomato	Cabbage	Okra	Eggplant	Summer squash	Potato	Lettuce	Spinach	Carrots	Onion	Radish	Total Number of
4	The Green Haven Project	2124.30						✓	✓	✓	✓		✓	✓	✓			7
5	St. Simon’s Farm	2337.17			✓	✓	✓		✓	✓	✓				✓	✓	✓	9
6	Baptist Hospital	3311.94	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓		✓	✓	13
7	Urban Farming Institute	358.95			✓		✓	✓		✓				✓	✓	✓		7
8	Harpke Family Farms	426.81					✓						✓		✓			3

UFID	Name	Area (m^2)	Sweet corn	Snapbean	Bell pepper	Cucumber	Tomato	Cabbage	Okra	Eggplant	Summer squash	Potato	Lettuce	Spinach	Carrots	Onion	Radish	Total Number of
9	Miramar Community Garden	430.54		✓	✓	✓	✓	✓	✓	✓	✓		✓	✓		✓	✓	12
10	Pembroke Pines Community Garden	519.81				✓	✓						✓		✓			4
11	Lauderdale Lakes Community Garden	888.32		✓	✓	✓		✓	✓	✓	✓		✓	✓		✓	✓	11
12	Rotary community garden of	1281.85		✓	✓	✓	✓			✓					✓		✓	7

UFID	Name	Area (m^2)	Sweet corn	Snapbean	Bell pepper	Cucumber	Tomato	Cabbage	Okra	Eggplant	Summer squash	Potato	Lettuce	Spinach	Carrots	Onion	Radish	Total Number of
	coral springs																	
13	Dania Beach Patch Community Garden	2389.80			✓		✓	✓		✓				✓	✓	✓		7
14	Highland Community Garden	3911.07			✓	✓	✓				✓		✓					5
15	Tree Amigos	5057.91			✓				✓					✓			✓	4

UF ID	Name	Area (m^2)	Sweet corn	Snapbean	Bell pepper	Cucumber	Tomato	Cabbage	Okra	Eggplant	Summer squash	Potato	Lettuce	Spinach	Carrots	Onion	Radish	Total Number of
16	Marando Farms and Ranch	8067.86		✓	✓	✓	✓			✓					✓		✓	7
17	Boca Raton Community Garden	345.85					✓						✓					2
√8	Henrietta Bridge Farm	440.63			✓		✓				✓		✓					4
19	Swinton Community Garden	615.03		✓	✓	✓	✓	✓	✓	✓	✓		✓	✓		✓	✓	12

UF ID	Name	Area (m^2)	Sweet corn	Snapbean	Bell pepper	Cucumber	Tomato	Cabbage	Okra	Eggplant	Summer squash	Potato	Lettuce	Spinach	Carrots	Onion	Radish	Total Number of
20	Cason Community Garden	817.37		✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓		12
21	Westgate Community Farm	1244.71			✓	✓		✓	✓	✓	✓		✓		✓	✓		9
22	Southwest Community Garden	1590.46		✓	✓	✓		✓	✓	✓	✓		✓	✓		✓	✓	11
23	Nicoya Farm	8040.60			✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	12

Table B3. Annual Food Production and Irrigation on Farm Crops

Name	Total max production ($kg \cdot yr^{-1}$)	Irrigation ($m^3\ yr^{-1}$)
Joseph Villari Victory Garden	1198.58	13,411.66
North Beach Community Garden	2370.852197	27,331.79
Pine Tree Park Community Garden	2181.488001	34,785.94
The Green Haven Project	6841.325957	94,037.66
St. Simon's Farm	9117.935513	102,123.83
Baptist Hospital	9891.405039	145,617.06
Urban Farming Institute	1393.40705	15,406.70
Harpke Family Farms	1584.304098	18,264.26
Miramar Community Garden	1447.77212	18,554.71
Pembroke Pines Community Garden	1928.650802	24,458.27
Lauderdale Lakes Community Garden	2805.363162	38,720.40
Rotary community garden of coral springs	5150.481743	57,175.63
Dania Beach Patch Community Garden	9085.288618	107,720.66
Highland Community Garden	12741.91121	135,336.21
Tree Amigos	20558.01916	218,625.04

Name	Total max production (kg•yr^{-1})	Irrigation (m^3 yr^{-1})
Marando Farms and Ranch	32416.78562	359,859.60
Boca Raton Community Garden	1265.540906	14,053.10
Henrietta Bridge Farm	1386.259345	19,694.70
Swinton Community Garden	2068.190599	26,506.03
Cason Community Garden	2423.549067	35,964.00
Westgate Community Farm	4155.293296	56,505.55
Southwest Community Garden	5022.777424	69,700.40
Nicoya Farm	27489.69178	338,000.98

* Crop types include sweet corn, snap pea, bell pepper, cucumber, tomato, cabbage, okra, eggplant, summer squash, potato, lettuce, spinach, carrot, onion, radish

$^{+}$ Values calculated from according to production per acre

Table.B4 Price of Crops (Source: USDA (2021))

Crops	Year	National Price ($·CWT^{-1})*	National Price ($·kg^{-1})*	Year	Florida Price ($·CWT^{-1})*	Florida Price ($·kg^{-1})*
Sweet Corn	2020	$ 37.50	$ 0.83	2020	$ 33.00	$ 0.73
Snap Bean	2020	$ 63.90	$ 1.41	2020	$ 55.00	$ 1.21
Bell Pepper	2020	$ 50.30	$ 1.11	2019	$ 67.50	$ 1.49
Cucumber	2020	$ 29.50	$ 0.65	2020	$ 22.90	$ 0.50
Tomato	2020	$ 57.10	$ 1.26	2020	$ 76.30	$ 1.68
Cabbage	2020	$ 20.80	$ 0.46	2019	$ 19.80	$ 0.44
Okra *	2001	$ 46.10	$ 1.01	2001	$ 54.00	$ 1.19
Eggplant	2001	$ 25.10	$ 0.55	2001	$ 33.50	$ 0.74
Summer Squash	2020	$ 40.90	$ 0.90	2019	$ 43.80	$ 0.96
Potato	2020	$ 13.23	$ 0.29	2018	$ 22.30	$ 0.49
Lettuce (Romaine)	2020	$ 31.30	$ 0.69	2000	$ 17.50	$ 0.39
Lettuce (Head)	2020	$ 30.80	$ 0.68		--	
Lettuce (Leaf)	2020	$ 51.20	$ 1.13	1998	$ 42.60	$ 0.94
Spinach	2020	$ 66.50	$ 1.46		--	
Carrot	2020	$ 28.90	$ 0.64	1998	$ 16.20	$ 0.36

Crops	Year	National Price ($\$\cdot CWT^{-1}$)*	National Price ($\$\cdot kg^{-1}$)*	Year	Florida Price ($\$\cdot CWT^{-1}$)*	Florida Price ($\$\cdot kg^{-1}$)*
Onion	2020	$ 14.50	$ 0.32		--	
Radish	2001	$ 38.90	$ 0.86	2001	$ 52.20	$ 1.15

* Fresh market price

Table B5. Carbon and water footprint factors

Crops	**Carbon Emissions (kg $CO_{2\text{-eq}}$·kg^{-1})**	**Water Emission factor(m^3·kwh^{-1})***
sweet corn	0.164	0.000288
Snap bean	1.2	0.000288
bell pepper	0.26	0.000288
cucumber	5.2009	0.000288
tomato	0.18	0.000288
cabbage	0.57	0.000288
okra	2.7	0.000288
eggplant	0.73	0.000288
summer squash	0.36	0.000288
potato	0.21	0.000288
Lettuce (Romaine)	0.38	0.000288
Spinach	0.13	0.000288
Carrot	0.22	0.000288
Onion	1.17	0.000288
Radish	0.39	0.000288

* Assuming coal generation for energy

Table B6. Rate for Stormwater, Wastewater and Water Use

County	Stormwater[a] ($\$\cdot 1000\ gal^{-1}$)	Stormwater ($\$\cdot m^{-3}$)	Reclaimed ($\$\cdot 4000\ gal^{-1}$)	Reclaimed ($\$\cdot m^{-3}$)	Wastewater[b] ($\$\cdot 4000\ gal^{-1}$)	Wastewater ($\$\cdot m^{-3}$)	Drinking water ($\$\cdot 4000\ gal^{-1}$)	Drinking water ($\$\cdot m^{-3}$)
Broward					37.58	2.47	24.90	1.64
Palm Beach					24.68	1.62	20.76	1.37
Miami-Dade					21.71	1.43	10.6	0.70
Average	**3.92**	**1.03**	**4.10**	**0.27**	**27.99**	**1.841**	**18.75**	**1.23**

[a] National Academies of Sciences(242) [b] UNC (314) in conjunction to UF

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