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Integrative technology hubs for urban food-energy-water nexuses and cost-benefit-risk tradeoffs (I)
Global trends and technology metrics

Chang, Ni Bin; Hossain, Uzzal; Valencia, Andrea; Qiu, Jiangxiao; Zheng, Qipeng P.; Kaandorp, Chelsea; Abraham, Edo; ten Veldhuis, Marie Claire; van de Giesen, Nick; More Authors

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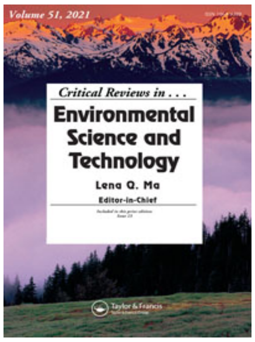

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Integrative technology hubs for urban food-energy-water nexuses and cost-benefit-risk tradeoffs (I): Global trend and technology metrics

Ni-Bin Chang [a], Uzzal Hossain[a], Andrea Valencia[a], Jiangxiao Qiu[b], Qipeng P. Zheng [c], Lixing Gu[d], Mengnan Chen[c], Jia-Wei Lu[e], Ana Pires[f], Chelsea Kaandorp[g], Edo Abraham[g], Marie-Claire ten Veldhuis[g], Nick van de Giesen[g], Bruno Molle[h], Severine Tomas[h], Nassim Ait-Mouheb [h], Deborah Dotta[h], Rémi Declercq[i], Martin Perrin[i], Léon Conradi[i], and Geoffrey Molle[j]

[a]Department of Civil, Environmental and Construction Engineering, University of Central Florida, Orlando, Florida, USA; [b]School of Forest Resources and Conservation, Fort Lauderdale Research and Education Center, University of Florida, Davie, Florida, USA; [c]Department of Industrial Engineering and Management Science, University of Central Florida, Orlando, Florida, USA; [d]Florida Solar Energy Center, University of Central Florida, Cocoa, Florida, USA; [e]Ministry of Ecology and Environment, South China Institute of Environmental Sciences, Guangzhou, China; [f]MARE - Marine and Environment Sciences Centre, Departamento de Ciências e Engenharia do Ambiente, Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal; [g]Department of Civil Engineering and Geoscience, Delft University of Technology, Delft, Netherlands; [h]IRSTEA, National Research Institute of Science and Technology for Agriculture and Environment, Montpellier, France; [i]ECOFILAE, Montpellier, France; [j]ECOSEC, Montpellier, France

ABSTRACT

The Food-Energy-Water (FEW) nexus for urban sustainability needs to be analyzed via an integrative rather than a sectoral or silo approach, reflecting the ongoing transition from separate infrastructure systems to an integrated social-ecological-infrastructure system. As technology hubs can provide food, energy, water resources via decentralized and/or centralized facilities, there is an acute need to optimize FEW infrastructures by considering cost-benefit-risk tradeoffs with respect to multiple sustainability indicators. This paper identifies, categorizes, and analyzes global trends with respect to contemporary FEW technology metrics that highlights the possible optimal integration of a broad spectrum of technology hubs for possible cost-benefit-risk tradeoffs. The challenges related to multiscale and multiagent modeling processes for the simulation of urban FEW systems were discussed with respect to the aspects of scaling-up, optimization process, and risk assessment. Our review reveals that this field is growing at a rapid pace and the previous selection of analytical methodologies, nexus criteria, and sustainability indicators largely depended on individual FEW nexus conditions disparately, and full-scale cost-benefit-risk tradeoffs were very rare. Therefore, the potential full-scale technology integration in three ongoing cases of urban FEW systems in Miami (the United States), Marseille (France), and Amsterdam (the Netherlands) were demonstrated in due purpose finally.

Abbreviations: FEW: Food-Energy-Water; GHG: Greenhouse gas; GREATS: Green, Resilient, Empowering, Adaptable, Transformative, and Sustainable; IRENA: The International Renewable Energy Agency; PV: Photovoltaics (solar); USEIA: U.S. Energy Information Administration; MWh: Megawatt hour; kWh: Kilowatt hours; PVS: Photovoltaic system; CSP: Concentrated solar power; SWH: Solar water heater; WER:

CONTACT Ni-Bin Chang nchang@ucf.edu Department of Civil, Environmental and Construction Engineering, University of Central Florida, Orlando, FL, USA.

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World Energy Resources; GW: Giga-Watts; BF: Biofuels; IEA: International Energy Agency; WP: Wood pellets; BP: Bioproducts; kg: Kilogram; EP: Electricity production; DU: Direct use; HP: Heat pump; LCOE: Levelized cost of electricity; PWh: Petawatt Hour; WtP: Wave energy to power; TB: Tidal barrage; DTP: Dynamic tidal power; SG: Stream generator; HA: Horizontal axis; VA: Vertical axis; DWT: Ducted wind turbines; SSB: Solid state batteries; FB: Flow batteries; FW: Flywheels; CAES: Compressed air energy storage; Th: Thermal storage; Hy: Hybrid technology; LID: Low Impact Development; RB: Retention basin; WDP: Wet detention pond; VNB: Vegetated natural buffers; B: Biofiltration systems; RI: Rainfall interceptor trees; ET: Exfiltration trench; TS: Treatment swales; PP: Pervious pavement; GR: Greenroof/cistern; NC: Natural area conservation; EL: Eco-friendly landscaping; ATSAT: Algal turf scrubber and anaerobic treatment; US: Underground storage; MAPS: Managed aquatic plant system; SH: Stormwater harvesting; BA: Biofuel – algae; GEM: Green environmental media; BAM: Biosorption Activated Media; IFGEM: Iron filings-based green environmental media; WTE: Waste-to-energy; SoSE: Systems of Systems Engineering; BESS: Battery Energy Storage System; BMP: Best management practice; FWT: Freshwater withdrawal technologies; CT: Centralized wastewater collection and treatment; DT: Decentralized wastewater treatment; PW: Potable water production; H: Hydroponics; A: Aeroponics; Aq: Aquaponics; V: Vericrop; MCS: Modular container system; CPS: Cubic production systems; VRT: Variable rate technology; DGPS: Differential global positioning system; WSNA: Wireless sensors networks–aboveground; WSNB: Wireless sensors networks–belowground; ASC: Automatic section control technology; SSVRI: Soil sensor and variable-rate irrigation; SDI: Subsurface drip irrigation; LO: Light optimization; RA: Rooftop agriculture; CG: Community garden; GEM: Green environmental media; VF: Vertical farming; PF: Peri-urban farm; IG: Industry greenhouse; IF: Indoor farming; ISGPG: Integrated solar-geothermal power generation; HFC: Hydrogen fuel cell; CPG: CO_2 plume geothermal power; BPSC: Bacteria-powered solar cell; MSTES: Molecular solar thermal energy storage; TL: Tidal lagoon; MSB: Molten salt battery; LHH: Low head hydro-turbine system; GS: Gravity storage; EE: Emerging energy; UA: Urban agriculture; WWT: Water extraction and wastewater technologies; SW: Stormwater; ES: Energy storage; W: Wind energy; T: Tidal energy; G: Geothermal energy; B: Bioenergy; S: Solar energy; DCIA: Disconnecting directly connected impervious areas; VIP: Laogang Venous Industrial Park; AD: Anaerobic digestion; PB: Plant breeding – trait selection; HES: High efficiency sprayer; HT: Hydrogel technology; PH: Pump and storage hydro-power system; WWTPs: Wastewater treatment plants; WDS: Water desalination; EIP: Eco-industrial parks; MUP: Municipal utility parks; CHP: Central heating plant; MG: Microgrid; HESS: Hydrogen Energy Storage System

KEYWORDS Cost-benefit-risk tradeoff; food-energy-water nexus; technology hubs integration

1. Introduction

Urban areas are modern hot spots that allow urban transitions and transformations to happen at multiple scales constrained by climate change (Grimm et al., 2008). Fast population growth, rapid urbanization, economic development, and increased mobility requirements have exacerbated the stress of resource depletion in food, water, and energy sectors (Scanlon et al., 2017). Under the increasing concerns of climate change, this global trend has led to a need for the development of different centralized or decentralized Food-Energy-Water (FEW) infrastructure systems with different scales over different regions to improve sustainable development (Schlör et al., 2018; Zhang et al., 2019). One of the current challenges arises from the need for synergistic integration of versatile technology hubs, either existing or emerging, via different strategies in a FEW nexus, which emphasizes the interdependences and interconnections across food, water, and energy sectors in an urbanized region (Walker et al., 2014). Therefore, the synergies and tradeoffs among these FEW technology hubs are critical for sustainable resources management in urban and regional planning (Cai et al., 2018; Lambert et al., 2017). Understanding the scaling effect in these intertwined supply chains and demand-side management will certainly help determine a better urban and regional developmental framework in the emerging discipline known as *sustainable urban systems* or *urbanization science* (Grimm et al., 2008; Seto et al., 2012; Wicaksono et al., 2017). As part of the unified theory of urbanism (Bettencourt & West, 2010), such advancement takes advantage of system synergies and reduces barriers in cost-benefit-risk tradeoffs (Yan & Roggema, 2019).

Half of the world's population lives in an urban environment at present (United Nations, 2014). By 2050, the world's population is projected to grow up to 9.2 billion, and more than 70% of world's people will live in cities (United Nations, 2014). Rapid urbanization is likely to trigger stronger and faster economic growth due to higher frequencies of economic activities, leading to economies of scale (PBL, 2014). However, continuous urban sprawl will result in more reliance on concentrated food, water, and energy supplies, as well as a higher demand for land resources. Given the growing demands of these three fundamental resources in urbanized regions, advanced systems analysis via a nexus paradigm for the three core sectors offer a great opportunity for advancement in technological, managerial, geographical, socioeconomic, and cultural domains. However, the intrinsic interdependences (the sufficient condition) and external interconnections (the necessary condition) among the three sectors in a legitimate nexus may ultimately compound the total solution. The situation is even more confounding when more sectors, such as the waste management sector, need to be included as an integral part of the nexus analysis. It is thus critical to perform strategic planning for technology hub integration in each FEW nexus, characterizing and tailoring each nexus to transform urban metabolisms with differing paces, conditions, and features (Walker et al., 2014). However, the optimal integration of existing and emerging technologies in each unique FEW nexus for different types of cities has not yet been fully understood and compared across the globe. The best alternatives for technology hub integration that enhance resource availability and utilization in each of the three sectors are defined as the 'Optimal Integration of Technology Hubs' in this study.

Optimal integration of food, water, and energy resources in a synergistic form to decrease water (Chinese et al., 2017), carbon (Kibler et al., 2018), and ecological footprints during the mobilization and utilization of these resources is a prerequisite for sustainable urban development. A deepened consideration of the optimal integration of these resources via different governance structures and functions can help increase community resilience against global challenges aggravated by climate change, fast economic development and globalization, rapid population growth and migration, and unprecedented resource depletion (Givens et al., 2018). Optimal integration of existing and emerging technologies in different types of FEW infrastructures in a city can be evaluated by highlighting and prioritizing the prerequisite parameters/indicators in order to achieve a synergistically balanced profile of cost-benefit-risk from a "systems of systems engineering (SoSE)" perspectives. These indicators may include, but are not limited to, water consumption, energy requirement, food production and demand, water footprints, carbon emissions, ecosystem services, environmental justice, and social equity. With increasing threats from resource depletion and climate variability, the competition for resources by misplaced populations is becoming a fundamental barrier for ensuring food, energy, and water security from a political economy perspective (Al-Saidi & Elagib, 2017). This also triggers a need to explore sustainable pathways that enhance resource efficiency at a well-structured and well-designed urban FEW nexus, evaluate cost-benefit-risk tradeoffs, enhance social equity and environmental justice, and improve urban resilience and sustainability. Therefore, the overarching goals of this type of engineering system analysis are to (1) search for synergistic pathways toward food, energy, and water security on the basis of circular economy in these tailored FEW nexuses (D'Odorico et al., 2018) as well as (2) identify and justify insightful cost-benefit-risk tradeoffs with sound decision analyses among engineered food, energy, and water infrastructure systems to minimize social, economic, and environmental impacts. As technological advancements are moving forward at a rapid pace, the optimal integration of technology hubs via green engineering or industrial ecology has become an indispensable and promising tool to achieve overarching goals of sustainability.

This analysis requires understanding different existing and emerging technologies as well as assessing the optimal solution for each type of FEW nexus with extensions through varying future scenarios. Optimal integration must comply with numerous technical constraints (e.g., costs, risks, etc.) in order to achieve maximum benefits while managing FEW supply chains substantially and sustainably. Although different existing technologies are oftentimes separately used in nexus studies, the optimal integration of existing and emerging technologies considering costs, benefits, and associated risks has not been extensively studied in contemporary literature. Few of the previous studies have attempted to holistically consider the adoption and adaptation of different technology hubs in varying FEW nexuses across different planning contexts with changing spatial and temporal scales. Therefore, this paper aims to generate contributions by identifying the potential integration of technology hubs in a FEW nexus with respect to possible tradeoffs related to costs, benefits, and risks at various spatiotemporal scales. We emphasize that technology hubs could play a crucial role in a FEW nexus, as the integration of technologies in different sectors is a key step to success in a variety of FEW infrastructure systems at different spatiotemporal scales.

Given the highlights for urban sustainability provided in the Introduction section, the remaining part of this paper is organized as follows: Section 2 briefly summarizes the importance of a FEW nexus approach for urban infrastructure planning with respect to technology metrics; Section 3 discusses the integration of decentralized and centralized technologies, including both existing and emerging technologies, with their cost-benefit-risk factors in a FEW nexus; Section 4 provides insights of systems analysis with implications for industrial ecology and convergence science; and Section 5 explores final observations of cost-benefit-risk tradeoffs for comprehensive technology hub integration of this study.

2. Study methodology

In response to this contemporary call, numerous studies have focused on different aspects of the development and implementation of a nexus approach for FEW infrastructure planning by analyzing the changing interconnected and interdependent FEW frameworks in literature. However, the cost, benefit, risk factors, and their associated socioecological and environmental impacts are intimately tied to decision making through either bottom-up or top-down approaches within differing governance structures. As the operations of these three sectors are driven by existing and/or emerging technologies under varying governance structures, the tradeoffs among these three sectors have evolved over time toward more sustainable development (Daher et al., 2017; Pahl-Wostl, 2019). These operational efforts have inevitably led to some prevailing nexus analyses, integrative philosophies, and case-specific applications across the globe.

For example, some nexuses only highlighted water resources (Daher, Hannibal et al., 2019; Larsen & Drews, 2019; Rosa & D'Odorico, 2019), food production (Abdelkader et al., 2018; Neto et al., 2018; Zhang, Campana et al., 2018), or energy generation (Mroue et al., 2019; Nouri et al., 2019; Wang, Fath et al., 2019), with few interdependent relationships. Others focused on case-based engineering practices integrating food-water or water-energy systems (Di Felice et al., 2019; Engström et al., 2017;

Hanes et al., 2018; Wang et al., 2017; Wicaksono & Kang, 2019). Nevertheless, new knowledge has been found in terms of varying analytical frameworks, governance structures, social networks, managerial policies, engineering workflows, political surveys, and methodological footings by synthesizing existing nexus-related studies (Covarrubias et al., 2019; Daher, Lee et al., 2019; Fan et al., 2019; McCallum et al., 2020; Meng et al., 2019; Newell et al., 2019; Zhang, Chen et al., 2018). On the other hand, a decoupling process may help produce new knowledge as well. This is especially true in agricultural production with respect to technology adaptation and improvements of food production, processing, and distribution (Dozier et al., 2017). In conventional irrigation, for example, the use of reclaimed wastewater instead of groundwater and fresh surface water reduces the life cycle greenhouse gas (GHG) emissions for strawberry, lemon, celery, and avocado production by 14%, 7%, 59%, and 9%, respectively, in Ventura County, California (Bell et al., 2018). The reuse of treated wastewater in urban agriculture can reduce 33% of total GHG emissions compared to GHG emissions from untreated wastewater diluted in surface streams; such actions can directly save groundwater consumption in a FEW system in the sense that a cost-benefit-risk tradeoff does exist among water reuse, food production, and GHG emissions (Miller-Robbie et al., 2017).

In order to promote urban sustainability in food, water, and energy supplies, numerous technologies have been developed and adopted independently or collectively, while others are currently being proposed, innovated, and gradually developed. Synergizing separate technologies in the food, energy, and water sectors are thus critical for understanding the nexus paradigm of different FEW systems. The philosophical streamlines of the optimal integration of technology hubs for FEW systems are shown in Figure 1. In the technology metrics, the engineered system is centrally located, with different technologies connected for the proper management of food, water, and energy resources toward creating Green, Resilient, Empowering, Adaptable, Transformative, and Sustainable (GREATS) urban development. With the continuous advancements of technology hubs, sustainable urban FEW resource production and management may help enhance the security of food, energy, and water supplies and avoid resource depletion. Applied systems analysis of FEW nexuses not only supports a holistic understanding of sustainable resource planning and management, but also explores potential strategies for both technology advancements and governance structures constrained by cost, benefit, and risk factors for improving urban sustainability (Dai et al., 2018).

According to the principle of SoSE, a technology-based solution in each sector requires an integrative connection to solutions in other core sectors

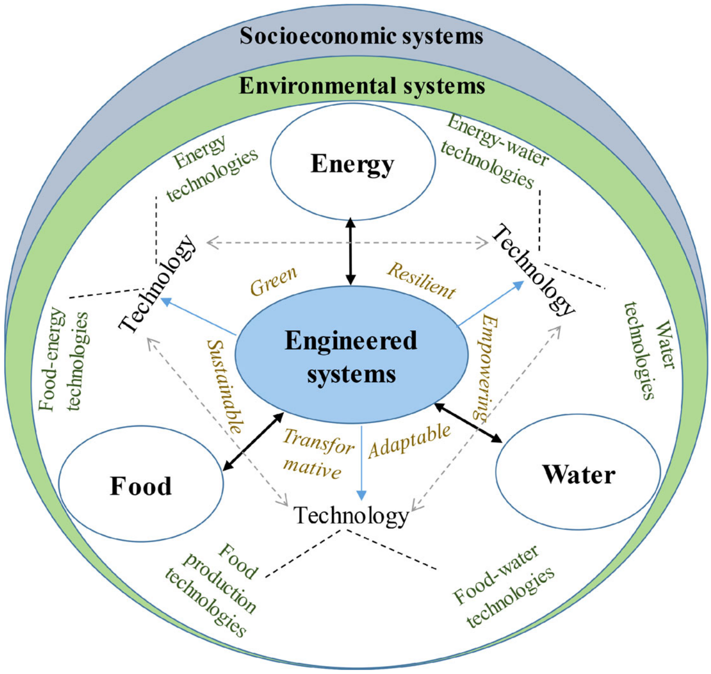

Figure 1. Integrated technology hubs of the FEW nexus systems.

in a complex and large-scale FEW system, and thus there is an acute need for optimal technology integration to improve community resilience as a total solution in each unique FEW nexus with scales. This would in turn trigger the need to identify interconnected and interdependent relationships among technology development driven by governance structures and policies (Kaddoura & Khatib, 2017). In this study, a multistage analysis was conducted to lay down the comprehension of GREATS via searching, screening, and analysis of both existing and emerging technologies. This required a thorough review of the scientific literature, focusing first on the emerging and existing technologies. Various technical and managerial reports associated with FEW technologies were identified and screened, and potential FEW technologies, along with their global trends (Figure 2), were summarized for developing the important technology metrics over the FEW sectors for possible technology integration. As the hierarchy of all the streamlined technology hubs in a generic FEW nexus was structured in Figure 2, technology codes used for this study were listed in Appendix A for future applications. Some of the decentralized technologies may be combined into the centralized technologies in sequence and/or in parallel on an as-needed basis. An extensive overview of different FEW technologies with a comparative analysis related to associated costs, benefits, and risks can then provide cross-linked clues for the possible optimal integration of technology hubs. Implementation of some existing technologies was

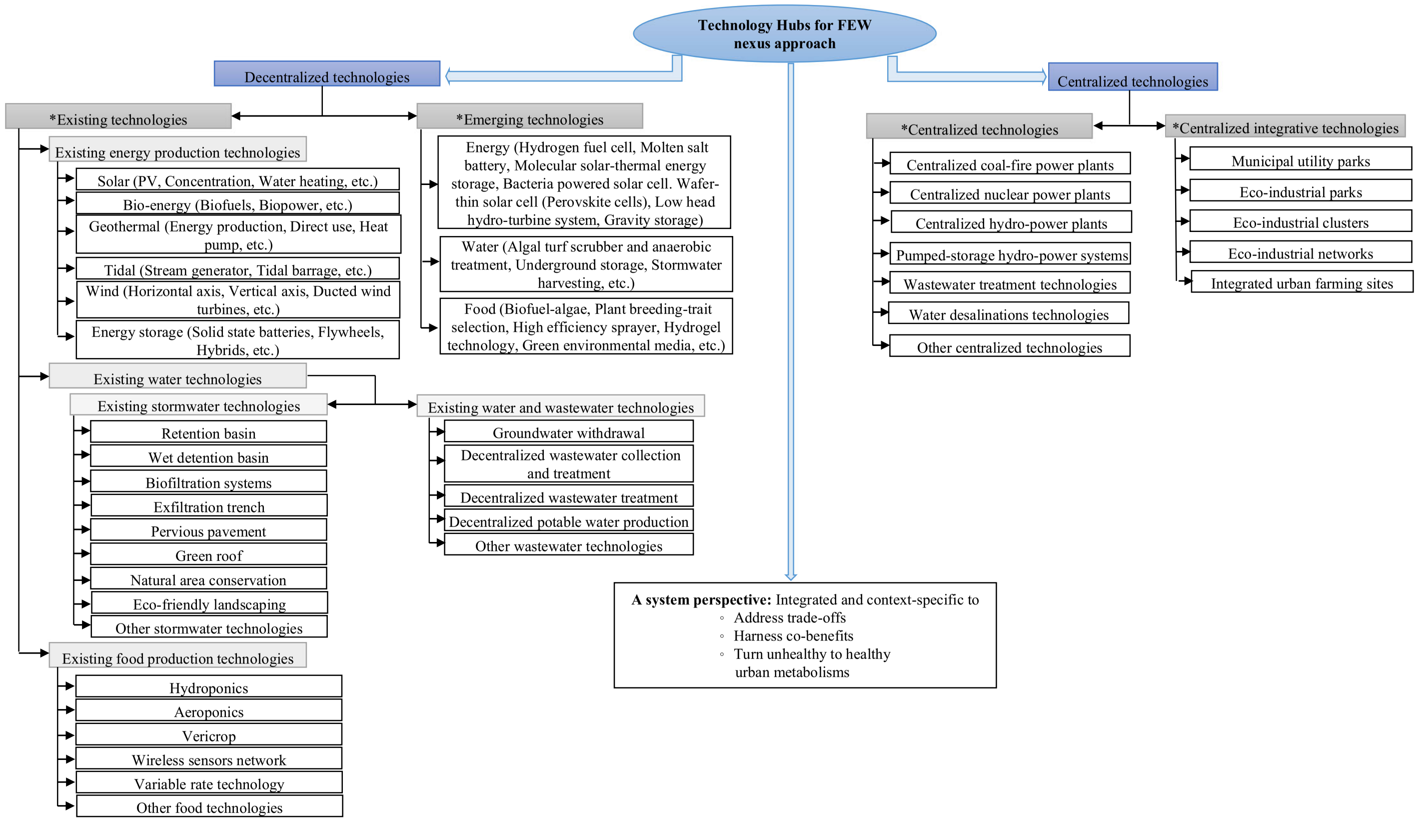

Figure 2. Technology metrics related to the FEW nexus in this study.

highlighted based on well-known case-specific applications using a set of demonstrated case studies throughout the world.

3. Results and discussion

3.1. Integration of technology hubs for an urban FEW nexus

As mentioned above, the FEW sectors in a nexus are interconnected and interdependent via complex interactions with varying spatiotemporal scales (Gragg et al., 2018). Due to the continuous emergence of new technologies and the rapid development of synergistic operations among innovations, the best available technological solution depends on the limiting resources in each unique FEW nexus. Evolution of FEW nexuses enhances and transforms the urban metabolism to be more cost-effective and sustainable (Walker et al., 2014). For example, technology hubs in the agricultural section may include those for urban agriculture and food production, such as rooftop agriculture or vertical farming irrigated by surface water or groundwater, etc. When these technologies are adopted and coordinated in the agricultural sector at a small scale, they can be referred to as decentralized technologies. However, different regional and urban farming technologies for both food and biofuel production can be integrated for more than one sector (e.g., food and energy sectors) at a much larger scale to create synergistic effects, which would then be considered centralized technologies. This achievement can be further extended to include a water sector via the inclusion of geothermal systems to sustain the irrigation for food and biofuel energy generation and storage with the aid of irrigation using reclaimed wastewater and geothermal circulation using reused stormwater. Collective adoption of the integrated FEW technologies above enhances production efficiency, resource conservation and recycling, pollution prevention, and waste minimization, while promoting environmental, social, and economic sustainability.

In fact, each FEW system might have a wealth of alternatives for the present or future. However, the optimal integration of these technologies via cost-benefit-risk tradeoffs with respect to sustainability indicators for different centralized or decentralized FEW systems turn out to be the most challenging task for urban sustainability in the modern nexus paradigm (Lee et al., 2017). For instance, as several FEW technologies are still in their incipient stages of development and commercialization in urban FEW systems, some of them may soon have the potential to reshape different decentralized or centralized FEW systems. Some emerging FEW technologies may lead to a turning point in either a stand-alone or a coupling mode within a FEW nexus, regardless of whether it exists as a hierarchical framework (e.g., bottom-up or top-down). Based on the technology hubs presented in Figure 2, the next section describes the metrics of different technology hubs for different urban FEW systems in terms of decentralized vs. centralized characteristics, and existing vs. emerging natures across the three sectors in detail.

3.2. Decentralized technologies for urban FEW systems

This section describes the existing technologies for green or renewable energy harvesting (excluding conventional power generation systems such as burning coal, oil, natural gas, and nuclear fuel), water (including both wastewater and stormwater treatment technologies), and urban farming/food production that are highly relevant to urban FEW systems.

3.2.1. Existing technologies for FEW systems

3.2.1.1. Energy technologies for FEW nexus systems. Considerable energy is required for agricultural activities, production and delivery of fertilizers, irrigation, and food processing and supply-chain. Integrating nonrenewable and/or renewable energy technologies as well as stormwater reuse in the water and agricultural production sectors can enhance water and food security. Technologies of renewable energy production including wind, solar, geothermal, and hydropower/tidal energy with energy storage systems for enhancing urban sustainability have been advancing rapidly.

Renewable energy technologies can be efficiently adopted directly on-site (e.g., solar system for irrigations) or indirectly (biofuels for transportation) in different FEW nexuses. When applicable, 200 times less water is needed for solar photovoltaics (PV) or wind compared to a regular coal-fired power plant for the same energy outputs (IRENA, 2015), although initial installation costs might be higher. Overall, it is projected that energy generation will increase by about 3–5 times for bioenergy, 4–15 times for geothermal, 30–80% for hydro-energy, 7–25 times for solar PV, 20–350 times for concentrated solar power, and 4–12 times for wind power by 2030 compared to the actual production levels in 2011 (Ellabban et al., 2014), which are elaborated in detail below.

(1) Solar energy technologies

Technologies like solar PV devices and solar cells are used to capture the energy from sunlight and convert it directly into electricity for use in heating water for buildings, swimming pools, and greenhouses via solar thermal power plants (USEIA, 2019). The abbreviation associated with each type of technology is included in parentheses below to facilitate the discussion of technology hub integration later, and they are summarized in Appendix A. Descriptions of solar technologies such as photovoltaic system (S1-PVS), concentrated solar power (S2-CSP) and solar water heater (S3-SWH) are given in Supplementary Information (S1.1). The technological considerations, including the costs-benefits-risks of some of the solar energy technologies, are summarized in Table S1 (Supplementary Information).

(2) Bioenergy technologies

Bioenergy is a major source of renewable energy consisting of 14% out of 18% renewable energy in the energy mix and offering 10% of the global energy supply. These technologies are increasingly applied throughout the world. Through the adoption of different bioenergy technologies, biomass-derived syngas can be employed to produce thermal energy, electricity, and transportation fuels (WER, 2016), including using solid waste for power generation; biomass may grow to 270 GW in 2030 globally compared to 62 GW in 2010 (Ellabban et al., 2014). Detailed descriptions of some bioenergy technologies such as biofuels (B1-BF), biopower (wood pellets) (B2-WP) and bioproducts (B3-BP) are given in Supplementary Information (S1.1). Technological considerations, including the costs, benefits, and risks of some of the decentralized bioenergy technologies are summarized in Table S2 (Supplementary Information).

(3) Geothermal energy technologies

Geothermal, heat or thermal energy within the earth, is a clean and renewable source of energy, and is used for different applications such as heating water for bathing, heating buildings, and generating electricity. Due to its potential, the installed capacity of geothermal power plants is expected to grow to 140–160 GW by 2050 (Ellabban et al., 2014). Geothermal energy is green due to its insignificant CO_2 emissions compared to other technologies. According to the literature, carbon emissions are about 0.06 kg CO_{2e}/kWh for a single-flash power plant compared to 0.59 kg CO_{2e}/kWh for a natural-gas-fired power plant, and 1.13 kg CO_{2e}/kWh for a coal-fired power plant (DiPippo, 2012). Note that CO_{2e} is defined as the equivalent emissions of CO_2 when other greenhouse gases are involved. Descriptions of geothermal energy technologies such as electricity production (G1-EP), direct use (G2-DU) and heat pump (G3-HP) are given in Supplementary Information (S1.1). The technological considerations of some of the decentralized geothermal energy technologies are described in Table S3 (Supplementary Information).

(4) Hydropower technologies

As a potential renewable energy, run-of-the-river hydroelectricity is a typical type of hydropower that harvests the energy from flowing water to generate electricity via an impoundment facility. However, tidal power can also convert kinetic hydro-energy into power. With the rapid advancement of this technology, tidal energy potential has been estimated to be about 32 PWh/year globally (Rusu & Venugopal, 2019). Due to its huge potential, the European Union has planned to install capacities of 3.6 GW and

188 GW by 2020 and 2050, respectively (Segura et al., 2017). Since tidal energy technologies are still in an initial stage of development, environmental impact, cost-benefit, technological viability, and potential risks are yet to be thoroughly studied, although some successful cases have been reported (Segura et al., 2017). Several technology variations have been reported to provide cost-effective energy generation (shown in Supplementary Information Table S4). Some of these technologies may be considered centralized technology. Descriptions of hydro-power technologies such as tidal barrage (T2-TB), dynamic tidal power (T3-DTP), stream generator (T1-SG) and wave energy to power (T4-WtP) are given in Supplementary Information (S1.1), and the associated costs, benefits, and risks are shown in Table S4 (Supplementary Information).

(5) Wind energy technologies

As a recognized form of renewable energy, wind turbines convert kinetic wind energy into mechanical power, and the mechanical power is then transformed into electricity through a generator. With technological advancements, the installed wind power capacity has increased from 17.4 GW in 2000 to 486 GW in 2016 (Enevoldsen et al., 2018). However, inconsistent power generation, high installation costs, technological constraints, and fatigue issues are major challenges for this technology (Saleem & Kim, 2018). Some of the decentralized wind energy technologies are described in detail in Table S5 (Supplementary Information). Descriptions of wind energy technologies such as horizontal axis (W1-HA), vertical axis (W2-VA) and ducted wind turbines (W3-DWT) are given in Supplementary Information (S1.1).

(6) Energy storage technologies

Energy storage (ES) technologies are developed and improved to ensure efficient management of power for creating a more resilient and cost-effective energy infrastructure. These technologies are considered integral and indispensable parts of effective, reliable, renewable, and resilient distribution units, as they are used to store energy. ES technologies have been continuously advanced to facilitate different field applications with varying energy storage scales (Hadjipaschalis et al., 2009) allowing increasing power plant reliability and transmittance and distribution at full capacity during peak demand. These ES technologies can operate in harmony with smart grids and smart meters to sell extra electricity back to a regional power grid system. Some decentralized energy storage technologies are described in Table S6 (Supplementary Information). Descriptions of ES technologies such as solid state batteries (ES1-SSB), flow batteries (ES2-FB), flywheels (ES3-FW), compressed air energy storage (ES4-CAES), thermal storage (ES5-T) and hybrid technology (ES6-H) are given in Supplementary Information (S1.1).

Overall, although high investment costs are required by S2-CSP (compared to other solar technologies), the levelized cost of electricity (LCOE) is much lower ($0.14 to 0.36/kWh). However, high land resources are required. The efficiency of this technology depends on geographic locations associated with varying radiation intensity (Supplementary Information Table S1). On the other hand, much higher investment costs are required for bioenergy technologies, which have lower energy output compared to fossil fuels (Supplementary Information Table S2). Similarly to solar energy, geothermal energy technologies have higher installation costs, but can provide steady and reliable energy supplies and can be implemented in remote areas for a wide range of applications (e.g., G1-EP, G2-DU, and G3-BP). However, depending on the geographical locations, these geothermal technologies are affected by several factors such as seasonality effect, ground temperature, and thermal properties (Supplementary Information Table S3). Tidal energy is relatively cheaper, predictable, and scalable, although higher investment costs are required (Supplementary Information Table S4). No/less fuel is required for wind energy technologies, although these are associated with lower energy efficiency (Supplementary Information Table S5). ES technologies are mostly emerging, fast changing, scalable, reliable, higher power density, safe, and highly efficient, but very costly, and the environmental impacts of their production, use, and end of life disposal/ treatment have yet to be assessed (Supplementary Information Table S6). The selection of such ES technologies would be geographically dependent and application oriented.

3.2.1.2. Water technologies for FEW nexus systems. To understand the interactions among the FEW sectors in relation to urban resilience in a designatory and combinatorial domain, this section describes how communities can incorporate better planning scenarios by linking interdependent infrastructures such as Low Impact Development (LID) facilities to improve urban farming, flood control, and water quality management simultaneously in a fast growing urban region where the green-blue-gray water infrastructure system has to be cohesively built and in which the centralized stormwater sewer system is an integral part of the entire water sector. The technological considerations of some of the LID technologies related to stormwater and decentralized wastewater treatment for agriculture irrigation after reclamation are described in Tables S7 and S8 (Supplementary Information).

(1) Stormwater technologies

Stormwater technologies can be broadly categorized into (i) point-based LID, (ii) linear-based LID, (iii) area-based LID, and (iv) other LID technologies. Descriptions, including the costs, benefits, and risks of those LID technologies, are given in the Supplementary Information (S.1.2), and an example of each category of stormwater technologies is highlighted in this sub-section.

(i) Point-based LID technologies

Retention basin (SW1-RB). Retention basins are recessed areas within the landscape. They are designed for storage and retention of runoff volume to enable infiltration to the groundwater through permeable soils. Dry retention basin is an effective technique for flood control and water quality management. The adoption of retention basins as a network can optimize 20% cost savings compared to a single system (Travis & Mays, 2008). Descriptions of other point-based LID technologies such as wet detention pond (SW2-WDP), vegetated natural buffers (SW3-VNB), biofiltration systems (SW4-B), and rainfall interceptor trees (SW5-RI) are given in Supplementary Information (S1.2).

(ii) Linear-based LID technologies

Exfiltration trench (SW6-ET). An exfiltration trench temporarily stores and helps infiltrate stormwater. This technology is a subsurface retention system comprised of a perforated or slotted pipe acting as a conduit, contained by natural soil or synthetic aggregate. This technology is an effective LID facility for treating runoff from highways, big parking lots, and communities (Hajar, 2012). Descriptions of other linear-based LID technologies such as treatment swales (SW7-TS) are given in Supplementary Information (S1.2).

(iii) Area-based LID technologies

Greenroof/cistern (SW9-GR). Greenroof refers to a vegetated roof used for stormwater collection and infiltration. The infiltrate is stored in a cistern for reuse. In the cistern, the filtrate from the greenroof is collected and can be discharged to a downstream best management practice (BMP). Growth media and filtration media such as Biosorption Activated Media (BAM) (O'Reilly et al., 2012) for nutrient removal can be used to support greenroof for urban farming. If the greenroof is part of a stormwater treatment train, other LID technologies such as SW8-PP, used to reduce the runoff peaks, can be incorporated as integral parts of a green roof system (Joyce et al., 2017). Descriptions of other area-based LID technologies such as pervious pavement (SW8-PP) are given in Supplementary Information (S1.2).

(iv) Other LID technologies

Natural area conservation (SW10-NC). Protection of natural areas helps maintain the hydrological cycle of undeveloped areas by reducing runoff, fostering infiltration, and preventing soil erosion. Conservation areas include regions of undisturbed vegetation maintained at the development site, such as forests, floodplains and riparian areas, steep slopes, and buffers for wetland and shoreline.

Although they are highly geographically dependent, all stormwater technologies are cost-effective and highly efficient, handling renewable sources of water in the water sector for flood control over varying land use and land cover categories. These LIDs are also cost-effective for treating certain water pollutants effectively, such as nutrients, E. Coli, heavy metals, etc. Again, the proper use of such LIDs depends on the availability of land resources and landscape environments that may fit in different types of treatment train applications (Supplementary Information Table S7).

(2) Water extraction and wastewater technologies

Significant energy is required for water extraction from groundwater or surface water via the sequence of pumping, treatment and purification, and delivery of surface water using distributed pipelines for industrial, domestic, and agricultural use (Sharifzadeh et al., 2019). Thus, different sustainable technologies are still advancing for energy efficient water and wastewater treatment, supply, and use/reuse toward different applications, including in household consumption, renewable energy generation, and agricultural crop production (Supplementary Information Table S8).

Descriptions of water extraction and wastewater treatment technologies such as freshwater withdrawal technologies (WWT1-FWT), centralized wastewater collection and treatment (WWT2-CT), decentralized wastewater treatment (WWT3-DT) and potable water production (WWT4-PW) are given in Supplementary Information (S1.2). The costs of water extraction and wastewater treatment technologies are dependent on the pumping system, depth and pressure required, size of WWT plant and system, and the quality of raw water. Although effective for water recovery and reuse, high risk to public health due to micro-pollutants might be present, especially with WWT2-CT and WWT3-DT (Supplementary Information Table S8), which requires further assessment.

3.2.1.3. Urban agriculture technologies for FEW nexus systems. In fast growing urban regions, the concept of urban farming is increasingly popular for improving food security and efficient use of resources (e.g., land/space, recycling materials such as gray water, organic waste, light/solar energy, etc.), and enhancing the esthetic urban environment within the FEW nexus (Al-Kodmany, 2018). The technological considerations of some of the exemplary decentralized urban agriculture technologies with different scales are described in Table S9 (Supplementary Information), and a few representative technologies are highlighted in this sub-section.

(1) Production system technologies

Hydroponics (UA1-H). Hydroponics is a subgroup of hydroculture, a technique of growing vegetables using nutrients-based water solutions without any soil media. The plants can absorb and uptake dissolved nutrients efficiently from the hydroponics system, and thus hydroponics can be integrated with wastewater or stormwater treatment systems for nutrient removal and plant growth, or with other techniques including aquaponics, provided control of the solution is achieved (Li, Zhang et al., 2019). Descriptions of other production system technologies for urban agriculture in evolving FEW nexus systems such as aeroponics (UA2-A), aquaponics (UA3-Aq), vericrop (UA4-V), modular container system (UA5-MCS) and cubic production systems (UA6-CPS) are given in Supplementary Information (S1.3).

(2) Monitoring and maintenance technologies

Variable rate technology (UA9- VRT). Variable-rate technologies (VRT) are technological tools that enable producers to vary the rate of crop inputs (water, fertilizers, pesticides). A variable-rate (VR) control system and application equipment are integrated with this design to apply various inputs at precise times to achieve site-specific application rates of defined inputs at specific locations. A complement of components, such as a differential global positioning system (DGPS) receiver (for movable application tools), computerized maps, VR software, and controller are integrated to make VRT work with the aid of DGPS superimposed with crop development and inputs distribution maps. Examples of VRT applications for agriculture include fertilizer, lime, seeding, and pesticides. The technology can reduce material and labor costs, maximize productivity, and decrease the impact that over-application may have on the environment. A case regarding tomato production in the Netherlands showed that about 25% of pesticides and nitrogen-fertilizer use can be saved with the adoption of VRTs (Kempenaar et al., 2017). While traditionally used in large-scale industrialized farms, VRT could also be adopted in peri-urban farms. Descriptions of other monitoring and maintenance technologies for urban agriculture evolving FEW nexus systems such as wireless sensors networks–aboveground (UA7-WSNA), wireless sensors networks–belowground (UA8-WSNB), automatic section control technology (UA10-ASC), soil sensor and variable-rate irrigation (UA11-SSVRI), subsurface drip irrigation (UA12-SDI) and light optimization (UA13-LO) are given in Supplementary Information (S1.3).

(3) Integrated technologies

Rooftop agriculture (UA14-RA). A roof garden is a farming system on the roof of a structure or building. In addition to esthetic benefits, roof agriculture is potentially capable of providing food, hydrological benefits, energy saving, temperature control, habitat conservation for wildlife, etc. It may even have ecological benefits when adopted in a large-scale application. Rooftop farming is usually combined with greenroof, hydroponics, aeroponics, air-dynaponics systems, or container gardens. Case studies in Bologna (Italy) showed that this technology can potentially produce vegetables to satisfy 77% of the inhabitants' requirements during specific times of the year (Orsini et al., 2014). Descriptions of other growing-type technologies for urban agriculture in evolving FEW nexus systems such as community garden (UA15-CG), vertical farming (Sky farming) (UA16-VF), peri-urban farm (UA17-PF), industry greenhouse (UA18-IG) and indoor farming (UA19-IF) are given in Supplementary Information (S1.3).

Costs of urban agricultural technologies vary heavily depending on the type of technology; high investments are required for most of them (especially for the infrastructures), but there is potential for higher yields, and water and energy efficiency. For example, about 20 times less water is needed for UA1-H than the conventional soil-based farming (Supplementary Information Table S9). Although several risks are associated with urban agricultural technologies, such as plant death, continuous monitoring, technology failure, extreme weather, energy extensive, etc., the selection of suitable technologies together with LIDs and renewable energy technologies would be more effective in urban FEW nexus implementations.

3.2.2. Emerging technologies for food, water, and energy systems

3.2.2.1. Emerging energy technologies. The considerations for some of the emerging energy technologies in the proposed urban FEW nexus systems are given in Table S10 (Supplementary Information), and a brief description of hydrogen fuel cell as an emerging energy technology is described in this sub-section.

Hydrogen fuel cell (EE3-HFC) technology is an electrochemical energy conversion process used to convert chemical potential energy into electrical energy. In this system, hydrogen gas (H_2) and oxygen gas (O_2) are used as fuel through a proton exchange membrane cell. It is considered a nontoxic and renewable source of energy, provided H_2 and O_2 are obtained from renewable energy, and is applicable for transportation and other activities in various FEW systems. However, the presence of impurities, even trace elements in fuel, air streams, or fuel cell systems, could severely affect the anode, membrane, and cathode, which could dramatically reduce the performance (Cheng et al., 2007). Descriptions of other emerging energy technologies in evolving FEW nexus systems such as CO_2 plume geothermal power (EE1-CPG), bacteria-powered solar cell (EE4-BPSC), molecular solar thermal energy storage (EE5-MSTES), tidal lagoon (EE6-TL), molten salt battery (EE7-MSB), low head hydro-turbine system (EE8-LHH), and gravity storage (EE9-GS) are given in Supplementary Information (S2.1). Most of the emerging energy technologies are associated with higher investment costs, but are highly efficient. For example, EE1-CPG is about 10 times more efficient than the traditional system. Many of these are still unproven technologies in terms of long term efficiency, and technological and environmental risks, but researchers are working to resolve such issues (Supplementary Information Table S10).

3.2.2.2. Emerging stormwater treatment technologies. In light of the water or food scarcity issues in some FEW nexuses, the considerations for some of the emerging stormwater treatment technologies are given in Table S11 (Supplementary Information), and an example of algal turf scrubber and anaerobic treatment as an integrated emerging stormwater treatment technology for agricultural stormwater runoff in the crop fields and/or dairy farms is highlighted in this sub-section.

Algal Turf Scrubber and anaerobic treatment (ESW5-ATSAT). In this technology, algae biomass is grown through the uptake of nutrients from the stormwater runoff; the clean stormwater may be reused or recharged to groundwater and then the harvested biomass can be utilized for the generation of biodiesel and bioplastics. In addition, the harvested biomass can be fed into the anaerobic digesters and methane/hydrogen gas can be generated through the anaerobic digestion process. The integrated technology can be used for the recovery and reutilization of nutrients from contaminated river water/stormwater to support the generation of several types of algal biomass for energy and biofuel production (Bohutskyi et al., 2016). Descriptions of other emerging stormwater technologies in evolving FEW nexus systems such as underground storage (ESW1-US), managed aquatic plant system (ESW2-MAPS), stormwater harvesting (ESW3-SH) and disconnecting directly connected impervious areas (ESW4-DCIA) are given in Supplementary Information (S2.2).

3.2.2.3. Emerging urban agriculture technologies. For enhancing food security through urban farming, the considerations for some of the emerging urban agricultural technologies are given in Table S12 (Supplementary Information), and a few of the representative emerging urban agriculture technologies are summarized in this sub-section.

Biofuel – algae (EUA1-BA). Biofuel from algae is an alternative to liquid fossil fuels and other biomass sources, including corn and sugarcane. Algae can be grown with minimal impact on fresh water resources and can also be harvested using saline and wastewater. They are biodegradable. Although the per capita production cost of algae is higher compared to other biofuel crops due to high investment, maintenance, and operation costs, high yield (about 10–100 times more than other biofuel options) can be made possible (Bohutskyi et al., 2016). Research is still ongoing to develop cost-effective algae biofuels production at large scales, as this method could be an attractive alternative to corn and grain in the future.

Green environmental media (EUA5-GEM). BAM were developed and applied for nutrient removal through various LID technologies to deal with wastewater effluent, stormwater runoff, and agricultural discharge, including stormwater retention basins (O'Reilly et al., 2012) and linear ditches (Chang, Wen, McKenna et al., 2018). Recent developments of iron filings-based green environmental media (IFGEM) elevated the functionality of BAM, promoting the application potential of nutrient removal and recovery in terms of ammonia, phosphate, and nitrate simultaneously (Chang, Wen, & Wanielista, 2018). Once IFGEM can be applied at the field scale, nutrient cycling through the cost-effective treatment of stormwater runoff, wastewater effluent, and agricultural discharge for urban farming can be made possible to gain better cost-benefit-risk tradeoffs. Descriptions of other emerging urban agriculture technologies in evolving FEW nexus systems such as plant breeding – trait selection (EUA2-PB), high efficiency sprayer (EUA3-HES) and hydrogel technology (EUA4-HT) are given in Supplementary Information (S2.3).

3.3. Centralized technologies for Urban FEW systems

High-level technology integration has resulted in various centralized systems for sustainable resource management, including large-scale Eco-Industrial Parks (EIPs) and Municipal Utility Parks (MUPs). This advancement has generated a renewed pathway for sustainable development in many countries, which demonstrates a suite of urban FEW systems in the modern context of sustainable urban systems.

3.3.1. Centralized technologies

Some nontraditional centralized technologies are described in this section; their costs, benefits, and risks are summarized in Table S13 (Supplementary Information), and an example of water desalination as a centralized technology is highlighted in this sub-section.

Water desalination (CT3-WDS): Desalination is considered a potential solution for small, medium-, and large-scale water supplies when there is a shortage of freshwater, although it is very energy consuming. In the process, salt is removed from the brackish water or sea water to produce freshwater. Different technologies including reverse osmosis have been continuously improving the desalination process. Water desalination is especially crucial for regions with water scarcity, such as Middle Eastern countries, and can be coupled with wave/tidal energy and desert farming technologies to formalize unique FEW systems. From the energy use perspective, wastewater treatment, reclamation, and reuse rather than desalination, especially in arid or semi-arid regions, can be more cost-effective for agricultural crop production in various FEW systems (Sharifzadeh et al., 2019). Descriptions of other centralized technologies such as large-scale pump and storage hydro-power system (CT1-PH), large-scale wastewater treatment technologies (CT2-WWT), large-scale municipal incinerator technology (CT3-MIT), and large-scale municipal landfill technology (CT4-MLT) are given in Supplementary Information (S3.1). Most of them can be further integrated.

Although higher investment costs are associated with the centralized technologies, they are highly efficient with regard to energy recovery (CT1-PH) and water and resources recovery (CT2-WWT and CT3-WDS). Many of them are expensive (CT3-WDS), and carry a potential risk of contamination (CT2-WWT, CT3-MIT, CT4-MLT) (Supplementary Information Table S13).

3.3.2. Centralized infrastructure systems with industrial symbiosis

EIPs and MUPs can fall into this category, whereby the niche of a FEW nexus can be realized immediately or after mild expansion at the local or site scale. EIPs are industrial parks in which different industrial entities work in a symbiotic relationship to promote environmental, economic, and social sustainability through interactive material, energy, and information flows across FEW and other sectors. Different extended forms of EIPs, such as eco-industrial networks or clusters, can be developed in an attempt to carry out pollution prevention and waste minimization, environmental resource sharing (such as materials, water, energy, infrastructure, and natural resources), and information exchange and services. A MUP is defined as a park or any designated location that combines several utility components/systems such as CT2-WWT, CT3-MIT, CT4-MLT, etc. for use in an urban region. The formation of MUP should be investigated in the study of important social-ecological-infrastructure systems with respect to different geographic locations, firms, markets, governments, social movements, etc. Advances in the field of industrial ecology and urban ecology shed light on the opportunities to group some of these public infrastructure systems into a MUP to improve resilience, reduce risk, and even increase sustainability simultaneously. Both EIPs and MUPs could serve as technology hubs distributed in a centralized manner across urban regions to maximize the synergies and harmonize the tradeoffs in different FEW systems. Approximately 250 different types of EIPs (World Bank, 2019), along with limited MUPs, have been in operation or under development globally. A series of surveys of the EIPs and MUPs in different countries conducted by the authors are listed in Tables 1 and 2. A few of the demonstrated cases of centralized infrastructures with industrial symbiosis are briefly described in the following sub-sections.

3.3.2.1. Eco-industrial Parks. Some of the EIPs in different countries are described in this sub-section for demonstration.

(i) KALUNDBORG SYMBIOSIS, Denmark

Kalundborg symbiosis is the world's first eco-industrial park with an ever-increasing symbiosis relationship in a circular economy framework, in which the companies cooperate through mutualistic activities to provide social, economic, and environmental benefits. In this kind of industrial symbiosis network, different actors, including the Kalundborg municipality, the power company, the plasterboard factory, the pharmaceutical manufacturer, the enzyme producing company, the oil refinery, the waste management company, agriculture and fish farms, etc., are involved in a unique FEW system (Figure 3). Some of the industrial symbiosis activities include: (1) heat produced by the Asnaes Power Station is used for the city of Kalundborg. In addition, several factories, such as the Statoil Refinery, Novo Nordisk A/S, and Novozymes A/S use process steam produced by the Asnaes Power Station. About a 30% improvement in fuel utilization is achieved for the combined production compared to heat and power generation separately, (2) about 15% of the total process stream is received from the power generation unit that is used to heat oil tanks, pipelines, etc., in the Statoil Refinery, (3) steam from the Asnaes Power Station is also used to heat the processing plants in the Novozymes A/S and Novo Nordisk A/S, (4) a fish farm uses the cooling water from the power plant, and about 200 tonnes of trout and salmon is produced by the farm annually, (5) waste recirculation, such as fly ash from power plants, is sent to the cement industry to reduce the raw materials necessary for clinker production, etc. Due to the sharing of resources among the industrial units, the combined benefits of this EIP include: (1) bottom-line savings of 24 million EUR, (2) 14 million EUR in socioeconomic savings, (3) emission reduction of 635,000 tonnes of CO_2, (4) savings of 3.6 million m^3 water, (5) savings of 100 GWh of energy and 87,000 tonnes of materials every year (Ellen MacArthur Foundation, 2018).

(ii) Norrköping Industrial Symbiosis, Sweden

Norrköping's industrial symbiosis began with a waste-to-energy (WTE) plant (heat and power) established in 1982 by the Norrköping municipality, Sweden. The plant was upgraded to use biomass (early 1990s) and municipal and industrial waste in 2002 and 2010, respectively. Several factories and a municipality are involved in these symbiotic activities, for example,

Table 1. Examples of eco-industrial Parks.

Name	Location	Sources
North America		
ReVenture Park – Charlotte	North Carolina, USA	ReVenture Park (2019).
Devens Eco-Industrial Park	Boston, USA	Devens Eco-Industrial Park (2019).
Londonderry Eco-Industrial Park	New Hampshire, USA	Londonderry Eco-Industrial Park (2019)
Fairfield Ecological Industrial Park	Baltimore, Maryland, USA	Fairfield Ecological Industrial Park (2019)
Northwest Louisiana Eco-industrial Park	Shreveport, Louisiana, USA	Northwest Louisiana Eco-Industrial Park (2019)
Environmental Park (The Monterey Regional Waste Management District)	California, USA	Environmental Park (2019)
Intervale Eco-Industrial Park	Burlington, USA	Intervale Eco-Industrial Park (2019)
Eco-Industrial Park	Rosemount, USA	Eco-Industrial Park (2019)
Eco-industrial park in Midlothian	Texas, USA	Eco-Industrial Park in Midlothian (2019)
South America		
Santa Cruz eco-industrial park in Rio de Janeiro	Rio de Janeiro, Brazil	Veiga and Magrini (2009).
Europe		
KALUNDBORG SYMBIOSIS	Copenhagen, Denmark	Kalundborg Symbiosis (2019)
Norrköping Industrial Symbiosis	Sweden	Norrköping Industrial Symbiosis (2019)
Lidköping Industrial Symbiosis	Sweden	Lidköping Industrial Symbiosis (2019).
Crewe Green Business Park	UK	Crewe Green Business Park (2019)
Dagenham Sustainable Industrial Park	UK	Dagenham Sustainable Industrial Park (2019).
Hartberg Eco Park	Hartberg, Austria	Hartberg Eco Park (2019).
POMACLE-BAZANCOURT PARK	Reims, France	Pomacle-Bazancourt Park (2019).
THE DEUXSYNTHE PARK	Dunkirk, France	The DeuxSynthe Park (2019).
Industrial park of Salaise-Sablons	Lyon, France	Industrial park of Salaise-Sablons (2019)
LAMOTTE INDUSTRIAL PARK	Paris, France	Lamotte Industrial Park (2019)
Rotterdam	Netherlands	Baas and Korevaar (2010)
The Forssa Eco-Industrial Park	Finland	The Forssa Eco-Industrial Park (2019).
Ekomo: eco-industrial park	Ämmässuo, Finland	http://projects.mcrit.com/esponfutures/index.php/home/96-ekomo-eco-industrial-park-in-aemmaessuo-finland
ValuePark	Schkopau, Germany	ValuePark (2019)
Kemira Kemi	Helsingborg, Sweden	Allard et al. (2012)
The London Sustainable Industries Park	East London, UK	The London Sustainable Industries Park (2019)
Kolmenkulma EIP	Koukkujärventie, Finland	Kolmenkulma EIP (2019)
Eco-industrial park at Rantasalmi	Rantasalmi, Finland	Rantasalmi EIP (2019)
Dyfi Eco-Park	Wales, UK	Dyfi Eco-Park (2019)
Turin Environment Park	Turin, Italy	Turin Environment Park (2019)
Africa		
Sasolburg Eco-Industrial Park	Free State, South Africa	Sasolburg Eco-Industrial Park (2019)
Asia		
National Eco-industrial Demonstration Park	Urumqi, China	National Eco-Industrial Demonstration Park (2019)
ULSAN MIPO AND ONSAN INDUSTRIAL PARK	Ulsan, SOUTH KOREA	Kim (2017)
Zhengzhou Shangjie Industrial Park	Henan, China	Zhengzhou Shangjie Industrial Park (2019)
Kokubo Eco-industrial Park	Yamanashi Prefecture, Japan	Morikawa (2000)
Fujisawa Eco-industrial Park	Fujisawa City, Japan	Morikawa (2000)

(*continued*)

Table 1. Continued.

Name	Location	Sources
Thang Long Industrial Park	Vietnum	Thang Long Industrial Park (2019)
Kawasaki	Japan	Kawasaki (2019)
Nanhai Eco-Industrial Park	Guangdong, China	Not available
Macheon Eco-Industrial Park	Gyeongnam, South Korea	Kim (2007)
Suzhou Industrial Park	Jiangsu, China	Suzhou Industrial Park (2019)
Sino-Swiss Zhenjiang Ecological Industrial Park	Zhenjiang, China	Sino-Swiss Zhenjiang Ecological Industrial Park (2019)
Vietnam-Singapore Industrial Park	Ha Noi City, Viet Nam	Vietnam-Singapore Industrial Park (2019)
Guiyu National Circular Economy Industrial Park	Guangdong, China	Guiyu National Circular Economy Industrial Park (2019)
BANTAENG INDUSTRIAL PARK	BANTAENG, INDONESIA	Bantaeng Industrial Park (2019)
Jurong Island Eco-industrial Park	Jurong Island, Singapore	Pan et al. (2015)
SHANGHAI CHEMICAL INDUSTRIAL PARK	Shanghai, China	Shanghai Chemical Industrial Park (2019)
Dongguan eco-industrial park	Guangdong, China	Dongguan Eco-industrial Park (2019)

Argoethanol, started in 2001, which produces bio-ethanol from grains with high environmental performance; Svensk Biogas, started in 2001, which produces fuels for transportation; Econova, which has produced a wide range of goods from recycled materials since 2007; and Norrköping municipality (Mikkola et al., 2016). The synergy of this unique FEW nexus involving the WTE has direct and indirect flows. The WTE burns waste but also biomass residues. The steam is sent to the ethanol plant. However, there is no direct interdependence between these two plants (Figure 4).

According to Johnston et al. (2011), the establishment of a platform could be useful to promote co-operation and other symbioses. The industries, however, are trying to solve waste and energy obligations imposed by legislation without having a specific governing body (Mikkola et al., 2016). Berlina et al. (2015) also pointed out that the local proximity to large firms in related industries like paper and pulp industries offer the opportunity to develop a large cluster with the aid of other stakeholders such as universities and the municipality. In the near future, the symbiosis will enhance its network by incorporating the production of green industrial CO_2 through converting CO_2 from Agroetanol into industrial grade gas. Other potential symbiosis includes the production of wood pellets, bio-chemicals, lignin-based carbon fiber, wood fiber foams, etc., from sawmill by-products.

(iii) Lidköping Industrial Symbiosis, Sweden

The industrial symbiosis at Lidköping, Sweden started when the heating plant was commissioned in the mid-1980s to substitute district heating for the large number of boilers existing in the city. In 2000, the plant was upgraded to a central heating plant (CHP), and since 2012 the plant can process waste and by-products. The amount of municipal waste consumed by this CHP is 9,500 t/y, and it can generate 25 GWh/y of electric energy and 400 GWh/y of heat for use in the city and its surroundings. Steam is

Table 2. Examples of municipal utility parks.

Name	Location	Sources
North America		
Pasco County MUP	Tampa, USA	Not available
Pinellas County MUP	Tampa Bay, USA	Not available
Eastern Orlando MUP	Orlando, USA	Not available
Europe		
Waste Treatment Infrastructure in North Rhine-Westphalia, Germany	North Rhine-Westphalia, Germany	Green Economy Report (2018).
Multimunicipal system for waste management	Madeira Island, Portugal	Not available
Augsburg MUP	Augsburg City, Germany	Augsburg Innovations Park (2019)
Amsterdam MUP	Netherlands	Not available
Weurt MUP	Netherlands	Not available
Asia		
Integrated Waste Management Facility (proposed)	Singapore	AECOM (2019)
Laohukeng Environmental Park	Shenzhen, China	
Gao'antun Circular Economy Industrial Park	Beijing, China	Not available
Laogang Venous Industrial Park	Shanghai, China	
The Environmental Park	Shenzhen, China	Not available

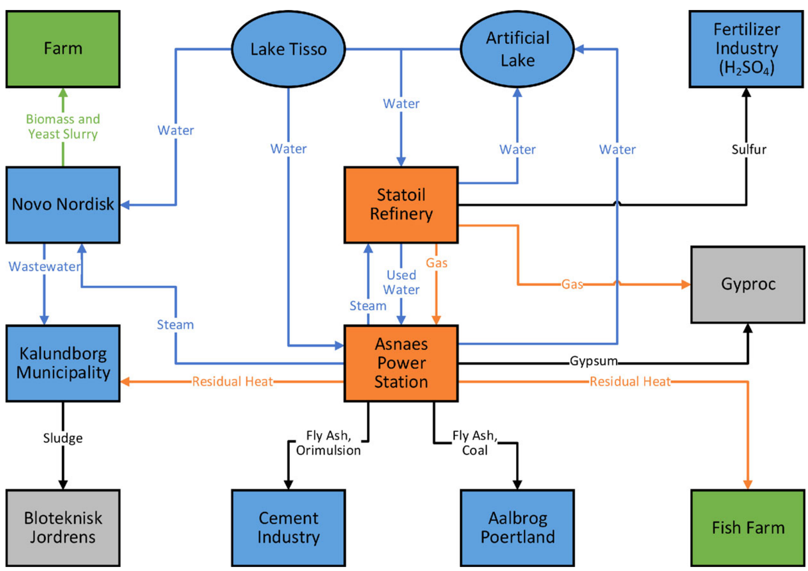

Figure 3. Kalundborg industrial symbiosis.

also generated (30 GWh) and, since 2011, has been sent to the bio-refinery plant, where the waste heat from the bio-refinery is sent back to the WTE (Angren et al., 2012).

Concerning the governance, there is no formal cluster in the Lidköping FEW system. However, the municipality is the actor involved in the communication and coordination of the different actors involved, as well as those that could potentially become involved, in the FEW nexus (Figure 5). Angren et al. (2012) discovered that possible synergies could include the

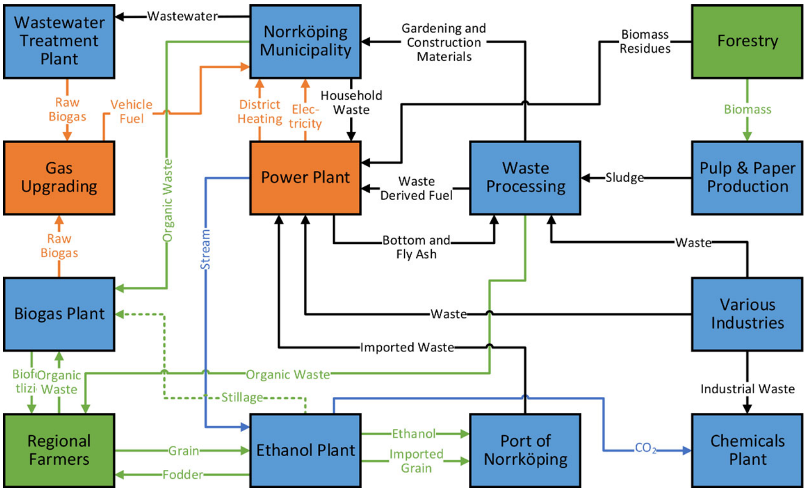

Figure 4. Norrköping industrial symbiosis networks.

recirculation of phosphorous through the use of sludge from the WWTP as a fertilizer, and the connection of the biogas plant to the central district heating system by using condensate and waste heat. Another possible synergy is to use carbon dioxide from the biogas plant of CHP in a greenhouse combined with manure or sludge to enhance plant growth (Angren et al., 2012).

In the future, the Lidköping FEW system plans to extend its networks to include a few more different symbiotic relationships, including the use of fly ash as input into cement production, the connection of district heating systems in a biogas plant, the use of organic waste (from farmland) as raw material for the biogas plant, the use of organic fertilizers (from the biogas plant) in crop production, and the recirculation of phosphorous (from sludges) to agricultural production.

The highlighted cases are the pioneered demonstrated cases of implemented centralized systems, in which different types of technologies from the technology hubs are implemented for synergistically producing energy and food (e.g., fish) while recovering and reusing water into the systems, and sharing resources, by-products, and residues among the intra-and interindustrial systems. For example, fly ash from coal fired power plants is sent to the cement industry for clinker production in the Kalundborg symbiosis. EIPs in Sweden mostly focused on resources recovery (materials and stream) from waste materials, and energy generation from waste incineration. In addition, some more existing and emerging technologies will be implemented in the future to develop more symbiotic relationships among different industrial systems (as discussed above).

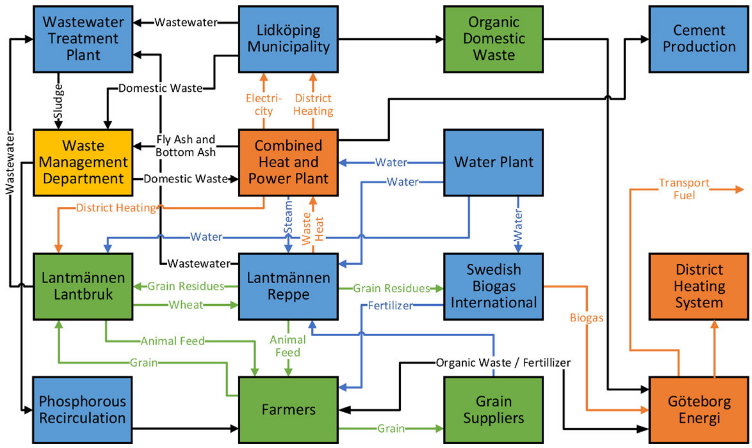

Figure 5. Lidköping industrial symbiosis network.

3.3.2.2. Municipal utility Parks. A MUP is made possible through energy exchanges and/or material flows and enhances resilience under regular conditions or contingencies. On a daily basis, the MUP may receive a certain amount of wastewater, raw water, stormwater, fuel, and solid waste. During contingencies, multiple MUPs can exchange all kinds of water, wastewater, solid waste, and fuel to improve the resilience of the MUP system regionally.

Although the exchange of water and energy flows has been well documented, recent challenges caused by the impact of climate change on agricultural areas have developed a tremendous amount of interest in the FEW nexus. As the buffer zones of MUPs or any open space among MUPs may be used for possible food production, farmland irrigation is likely to be carried out by using reclaimed water or stormwater collected in a MUP network. Urban resilience should be improved in this way with a diminishing rate of return due to the scaling effect. As examples, three MUPs across the world have been described here, and some others are provided in Supplementary Information (Part I: S3.2).

(i) Laogang Venous Industrial Park in Shanghai, China

Laogang Venous Industrial Park (VIP) is located on a beach in the eastern suburbs of Shanghai City, China. It plays a strategic role in waste treatment and disposal and is the largest MUP for waste management by area in China. At present, this VIP mainly deals with the solid waste stream with a capacity of 8900 Mg/d or more (Figure 6).

Laogang VIP has a WTE plant, three closed solid waste landfills, a solid waste landfill in service, an integrated landfill, a municipal WWTP, and a built-in WWTP. The combustion residues from WTE are disposed of in the integrated landfill, while the solid waste landfill is used for disposing of raw solid waste (Figure 6). Unlike other MUPs for waste management in

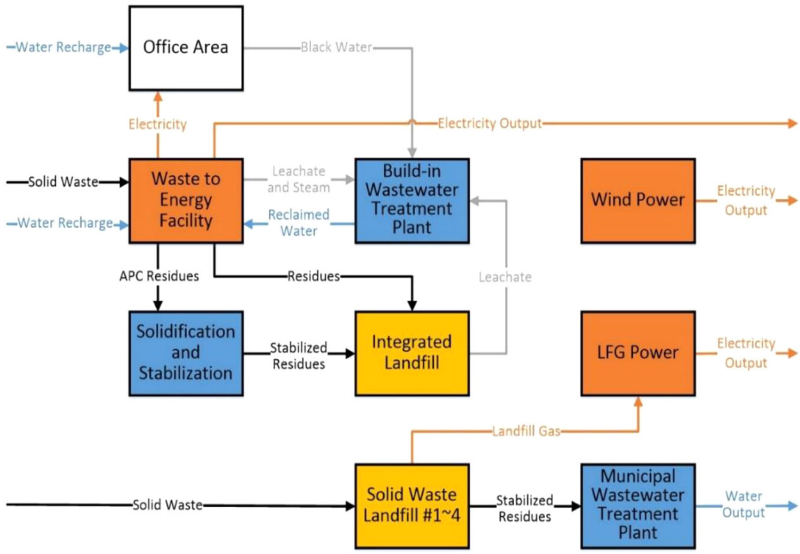

Figure 6. Laogang VIP Network.

China, Laogang VIP uses a municipal WWTP to treat the leachate from solid waste landfills. Moreover, half of this landfill leachate is shipped out to another nearby municipal WWTP because the municipal WWTP in the Laogang VIP is limited by capacity. However, the leachate from the integrated landfill is processed in the built-in WWTP and reclaimed for reuse in the WTE plant.

In summary, the most important feature of the Laogang VIP is that it has enough land to dispose of solid waste for the next fifty or one hundred years, at which point urban farming can be initialized if needed. In the future it may employ wind turbines to generate electricity in a larger quantity than the power generation from the landfill gas or the WTE plant. To improve energy recovery, a new WTE plant may be built soon, which has a capacity of 6000 Mg/d.

(ii) Augsburg, Germany

Augsburg city features an industrial symbiosis relationship between a WTE plant and an anaerobic digestion (AD) plant. The WTE can treat 200,000 t/y of waste and generates 38,008 MWh/y of heat and 78,085 MWh/y of electric energy. The AD can process 45,000 t/y of organic waste, leading to the generation of 13,800 m^3/y of fluid fermentation residue/surplus water, 18,300 t/y of solid residue, and 4,208,000 m^3/y of biogas. The exhaust air and biogas from AD are sent to the WTE for combustion, resulting in electricity generation. The thermal energy embedded in the steam condensation unit from the WTE power plant, which has a low temperature not suitable for district heating, is used to heat the digesters of the AD plant. The outputs from the AD plant include fluid fermentation, rejected products of fermentation, and refined fertilizer, which may serve as feedstock at the incinerator as fuel (Figure 7).

The industrial symbiosis started in 1994 when the WTE was commissioned. However, until 2013, when the AD began operating, the synergy with WTE was not formally interconnected in an industrial symbiosis relationship. This project was financed by the Bavarian Ministry for Environment to test three synergies in total. The focus of the study was the minimization of GHG emissions, including methane and nitrous oxide, from the AD plant. The current MUP was capable of reducing 64% of GHG emissions. To reach a higher reduction of GHG emissions from the AD plant, a reduction of GHG emissions in the processes of postcomposting, purification, and stabilization of the fermentation residue should be investigated.

(iii) Pinellas County MUP, Florida, USA

The MUP in Pinellas County includes the active Bridgeway Acres Landfill and the closed Toytown Landfill, which together generate a small amount of leachate. All stormwater, as well as water collected by the underdrain system of landfills, stays on site and is collected and stored in a stormwater/leachate pond (see Figure 8). The minimal quantity of actual landfill leachate is diluted by stormwater at this pond. The stormwater/leachate pond and the microfiltration/reverse osmosis unit, called Water Treatment Facility, support the production of boiler water for the operation of the boiler and cooling tower in a WTE. In this MUP, improving the resilience of the WTE can be fulfilled through integration with the stormwater supply. The reclaimed wastewater can be further treated via microfiltration and reverse osmosis and used as cooling tower water in the WTE facility. Unless the WTE plant is undergoing maintenance, the tonnage of waste sent to the landfill is minimal. In regular operation, this MUP processes the landfill incineration ash generated from the WTE at the dedicated ash monofill.

The implementation of MUPs is different geographically, but operates under similar principles (e.g., reuse waste materials, energy generation, and resources recovery), depending on the locally available resources and demand. For example, Laogang MUP in China is currently focusing on energy generation from waste materials but can evolve into a developed farming system with implemented renewable energy technologies in the future. Augsburg MUP processes both organic and inorganic waste to produce energy, and recover heat, water and residues from WTE and anaerobic digestion plant. In this symbiosis, materials, biogas, and residues are exchanged synergistically to improve efficiency and materials use, and GHG emission (discussed above). Pinellas County MUP has been recovering and reusing stormwater and leachate for reuse in the WTE plant as cooling water after intensive treatment.

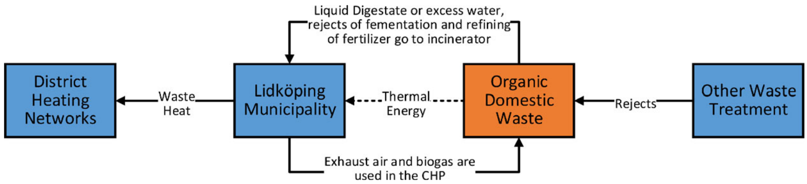

Figure 7. Principle of Augsburg MUP.

4. Insights for future urban FEW systems analysis

The overreaching goal of FEW nexus research is to not only synergize resources and facilitate tradeoffs but also produce new knowledge and trigger the development of innovative technologies via convergence science. This can be made possible by integrating science, engineering, and policy to promote sustainable development. Full scale cost-benefit-risk tradeoffs during the optimal integration of FEW technology hubs are expected to be practically implemented by differing decision-making processes under different governance structures. For an urban FEW nexus, validating emerging technologies and designing new technologies for the minimization of carbon, water, and ecosystem footprints in a city may result in a sustainable pathway for improving community resilience, from which the value chain of the new technologies can be better realized (Sperling & Ramaswami, 2018).

4.1. Cost-benefit-risk tradeoff in a FEW nexus system

A key question in this topical area is how we perform the cost-benefit-risk tradeoff in an optimization framework for a FEW nexus system. The implementation of technology integration in an urban FEW nexus is aimed at weaving existing and emerging technologies with respect to sustainable indicators such as carbon, water, and ecosystem footprints to realize the pros and cons in terms of cost, benefit, and risk. Such implementation can be observed and demonstrated for a hypothetical case of a few urban FEW nexuses in a coastal community. For demonstration, four alternatives can be organized in a coastal community with respect to the different technology hubs presented in Table 3. Alternative 1 proposes stormwater storage and harvesting for irrigation of green roof garden for urban food production. The stormwater storage can be a retention pond or an underground reservoir to collect treated stormwater. Solar PV is paired with an energy storage system to supply energy for operation of green roof irrigation and stormwater circulation. Surplus energy can be stored in the energy storage system or delivered to the power distribution grid via a smart meter. Alternative 2 has a greenhouse system along with an integrated stormwater harvesting and wind power system with an energy storage unit. Alternative

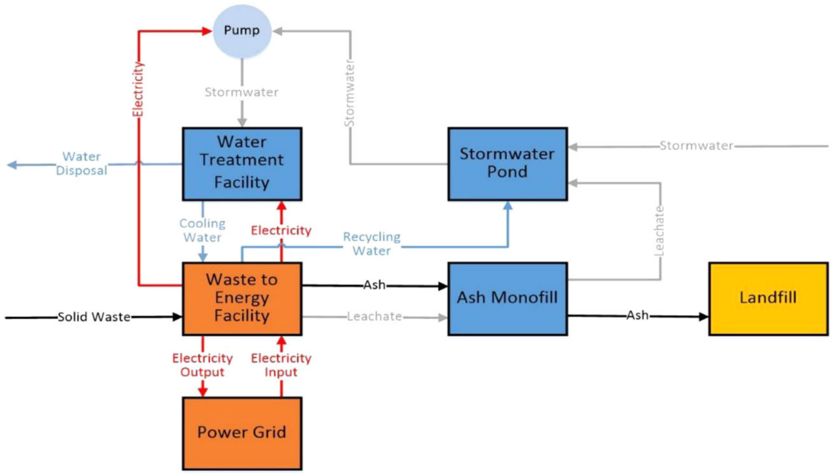

Figure 8. Pinellas County MUP network.

3 proposes stormwater harvesting, aeroponics, and biofuel production from food or waste to energy. The required food and waste can be supplied from crops cultivated for biofuel production or from local community waste streams. Although aeroponics minimize water consumption, the stormwater system does not change from the previous alternatives. Alternative 4 provides a different cultivation technique by proposing vertical farming supported by an integrated stormwater harvesting and ocean-wave energy production system.

The inclusion of renewable energy such as solar PV, wind, and ocean-wave energy (in coastal cities) enables the production of energy that can offset the community energy demands. This allows for greater independence of the electrical distribution grid, thus advancing energy resilience. Given the fluctuation between power generation of the renewable energy technologies and the power consumption of the community, the inclusion of an energy storage system is beneficial. In addition, having an energy storage system builds upon the community resilience through its capacity to store energy for utilization in unforeseen events, consequently reducing reliability on conventional power distribution system. Furthermore, the utilization of renewable energy decreases the environmental impacts associated with greenhouse gas (GHG) emissions, as well as water and ecosystem footprints correlated with the use of nonrenewable energy sources. These sustainable indicators can be understood through relation to cost-benefit and risk assessments, in which a cost-effective and sustainable solution can be realized in a multiobjective programing framework.

Taking advantage of the roof area in urban regions, distinct crops can be cultivated in a garden or a greenhouse. The water necessary for irrigation of the green roof can be supplemented with stormwater collected from a

Table 3. Coastal community technology hub alternatives.

FEW sectors	Food	Energy	Water
Alternative 1	Green roof garden	Solar PV system with energy storage	Stormwater storage and harvesting LID technologies
Alternative 2	Greenhouse	Wind system with energy storage	Stormwater storage and harvesting LID technologies
Alternative 3	Aeroponics	Biofuels (food and waste)	Stormwater storage and harvesting LID technologies
Alternative 4	Vertical farming	Solar PV, wind system, biofuels (food and waste), anaerobic digestion (wastewater) with energy storage	Stormwater storage and harvesting LID technologies

nearby stormwater pond, which can be stored in a storage tank (cistern) and recirculated for continuous irrigation in the FEW system. The use of stormwater harvesting for irrigation is crucial, as it reduces the water consumption and demand placed on groundwater and surface water supplies for non-potable water consumption. This provides an environmental benefit by reducing the stress on the water supply from the agriculture sector in urban areas. Additionally, the energy required for the pumping of stormwater and irrigation of crops can be supplied through renewable energy technologies, whereas cooling load reduction in the building can be expected from green roof implementation, which lowers the temperature inside the building. This results in reduction of energy necessary for cooling, which consequently also lowers the cost. Lastly, to complete the synergy in a FEW nexus system, the cultivation of crops can be aimed at biofuel producing crops for energy generation.

The strategies for deciding on the application of FEW systems encompass cost-benefit-risk tradeoff analyses for each proposed alternative. This decision-making process calls for optimization in the form of multiobjective programing models such as compromised programing models. The individual costs, risks, and benefits of the three FEW sectors are examined with respect to minimizing carbon, water, and ecosystem footprints (see Table 4 and Figure 9). Desirable systems exhibit minimal associated costs and risks, while maximizing benefits. Thus, the final goal is to select the technology hub alternative that satisfies the majority of the decision-making criteria. The implementation of the most appropriate technology alternatives is preferred to ensure the FEW nexus provides an economically beneficial, resilient, sustainable, and reliable community system.

4.2. Possible convergence opportunities for the future

Dealing with challenges facing humanity in the next century with regard to highly interdisciplinary FEW systems with varying scales require a suite of convergence opportunities. The following seven convergence opportunities

Table 4. Cost-benefit risk tradeoffs for technology hub alternatives.

	FEW sectors	Cost	Risk	Benefit
Alternative 1	Food (Green roof garden)	• -Low or minimal installation costs	• -Can be time consuming and laborious • -Crop growth competition	• -Stormwater runoff volume reduction • -Reduces water footprint associated with cultivation • -Nutrient recycling • -Decrease in heat island effect • -Building cooling load reduction
	Energy (Solar PV)	• -High installation cost • -Requires energy inverter and storage device	• -Low energy production efficiency • -Large ecosystem footprint (solar farm) • -Material is fragile	• -Reduction GHG and carbon footprint • -Diverse implementation • -Low O&M costs
	Water (Stormwater)	• -Cost associated with pretreatment	• -Accumulate pollutants from stormwater runoff	• -Water quality control (nutrient removal) and quantity control • -Low cost LID technologies • -Reduce reliance of surface and groundwater sources
Alternative 2	Food (Greenhouse)	• -High capital and O&M costs	• -Continuous maintenance and monitoring	• -Combined with other growing type technologies (vertical farming) • -Production is less vulnerable to the environment
	Energy (Wind power)	• -High capital and O&M costs	• -Site specific affecting energy production • -Difficulty in equipment transportation • -Noise pollution	• -Reduction GHG and carbon footprint • -High energy production efficiency
	• Water (Stormwater)	• -Cost associated with pretreatment	• -Accumulate pollutants from stormwater runoff	• Water quality control (nutrient removal) and quantity control • -Low cost LID technologies • -Reduce reliance of surface and groundwater sources
Alternative 3	Food (Aeroponics)	• -High initial cost and O&M	• -Can be energy intensive • -Production system vulnerable from change in growth	• -Suitable for many applications (garden, vertical and indoor farming) • -Minimization of irrigation and fertilization • -Reduction GHG and carbon footprint
	Energy (Biofuels)	• -High investment cost	• -Promote competition with food crops	

		• -Capturing and storage units	• -High water footprint • -Not applicable at all climates • -High ecosystem footprint from deforestation	• -Reduction GHG and carbon footprint • -Utilization of recycled organic materials and waste • -Alternative transportation fuel
	Water (Stormwater)	• -Cost associated with pretreatment	• -Accumulate pollutants from stormwater runoff	• Water quality control (nutrient removal) and quantity control • -Low cost LID technologies • -Reduce reliance of surface and groundwater sources
Alternative 4	Food (Vertical Farming)	• -High O&M costs	• -Requires additional technologies and process • -Energy consumption	• -Applicable in urban locations • -Minimization of irrigation • -Nutrient recycling • -High production yield
	Energy (Wave power)	• -High investment and O&M cost • -High cost for energy production • -Requires energy inverter	• -Not well-established technology (still under development) • -Application to coastal regions	• -Reduction GHG and carbon footprint • -High power-density energy generation • -Takes advantage of natural waves
	Water (Stormwater)	• -Cost associated with pretreatment	• -Accumulate pollutants from stormwater runoff	• Water quality control (nutrient removal) and quantity control • -Low cost LID technologies • -Reduce reliance of surface and groundwater sources

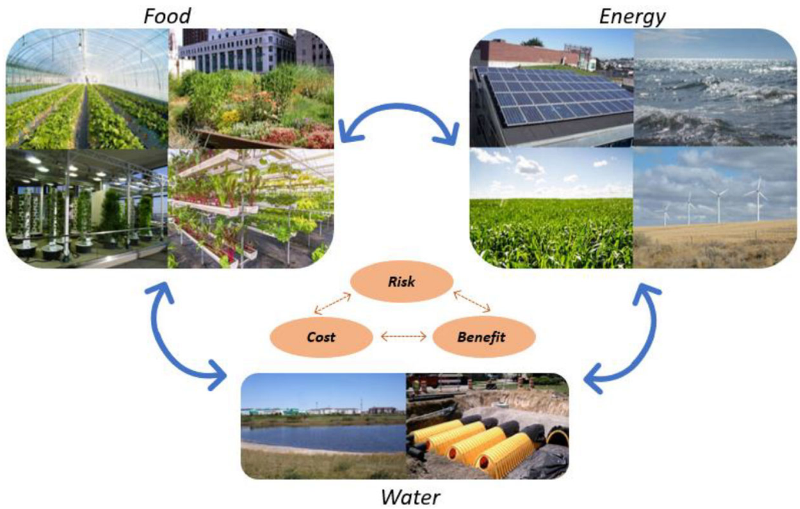

Figure 9. Cost-Benefit-Risk for Community Technology Hubs.

are representative of potential options, although more topics in convergence science can be identified in the future:

1. **Material Convergence Opportunities**: Advanced material science and technologies have an acute need for possible breakthroughs in energy storage of hydrogen gas and electricity, hydrogel applications for atmospheric water harvesting to support urban farming, and green environmental media for nutrient recovery as soil amendments or fertilizers through the stormwater runoff, wastewater effluent, and agricultural discharge. Any innovations in synthesis and processing routes to enable the novel development of hybrid composite materials, coating systems, metamaterials, and biomimetic hybrid materials can be helpful in exploiting the optimal integration of technology hubs in any FEW system.
2. **Energy Convergence Opportunities**: Scalable smart grids and innovative renewable and sustainable energy recovery and energy storage technologies are the priority research agenda globally. They include, but are not limited to, carbon capture and storage to reduce GHGs emission that may be advanced by CO2 conversion technologies to produce valuable chemicals (methanol, dimethyl ether, dimethyl carbonate, and formic acid) that can be further improved with possible catalytic or biocatalytic mediated approaches. This effort can lead to coupling the solid oxide fuel cells that produce electricity directly from oxidizing a fuel obtained from CO2 conversion technologies.
3. **Water Convergence Opportunities**: Efforts may focus on water reuse, resource recovery from water consumption and wastewater discharge,

energy and climate interactions affecting water supply and treatment, water monitoring and management in low income and resource limited urban or rural settings, and optimal water management constrained by limited energy supply to in turn improve the agricultural and energy production;

4. **Agriculture Convergence Opportunities**: Sustainable agriculture may improve the FEW systems via smart precision farming with the aid of sensing, informatics, and machine learning technologies that will in turn help produce drought or disease tolerant crops with the aid of genetic engineering technologies and convergence science, as well as promote sustainable materials management to make significant advancements in reduction, resource and biofuel extraction, recycling and beneficial reuse, sustainable disposal of domestic solid/organic waste streams, and food production and processing byproducts;
5. **Information Convergence Opportunities**: Data-enabled control and decision making for physical and embedded systems with the aid of sensors, internet of things, machine learning, big data analytics, and cloud computing can have a great potential to support precision agriculture, scalable smart grid, and optimal water management. GHG emission inventory can be a good platform for advanced systems analysis such as carbon credit trading, web-based interactive mapping, and urban/regional planning. It may support a network-enabled smart community or smart city (i.e., smart cyber-physical systems) in which the smart FEW systems are just an integral part.
6. **Decision Convergence Opportunities**: Decision analysis and data science in a sound data-system-society arena can help conduct the optimal integration of existing and emerging technology hubs as a breakthrough with potential solutions to better address cost-benefit-risk tradeoffs in a prespecified FEW nexus and resilience assessment of the applications of a sustainable systems framework to these and related themes of FEW nexuses.
7. **Environmental Convergence Opportunities**: Comprehensive industrial ecology evaluation is needed for critical social-ecological-infrastructural systems with centralized (MUPs and EIPs) or decentralized characteristics with the aid of multiple sustainability indicators. Such assessment metrics may cover environmental justice measures (environmental aspect), multi-level governance structures, social equity, and social network analyses (social aspect), and input-output analysis with the concepts of ecological economics, resources economics, and environmental economics (economic aspect) in all segments of a FEW nexus. This endeavor could trigger new concepts of biophysical, social science, and engineering integration via ontology analysis for better sustainability realization.

5. Conclusions

This paper addresses the challenges of food, energy, and water nexus research holistically to emphasize the importance of integrative technology hubs over three sectors. Numerous efforts have been undertaken to optimize the benefit/cost ratio and mitigate risk while improving synergies among technologies in the FEW nexus. The potential costs, benefits, and risks of associated technologies integrated into different nexuses presented in this paper (Part I), along with the three case studies presented in Part II (e.g. Miami, Amsterdam, and Marseille), are indicative of different spatial and temporal scales. Future challenges identified include: (1) the proper integration of existing and evolving technology hubs, (2) system identification, simulation, and optimization, (3) policy making and governance, and (4) adaptation with respect to cost, benefit, and risk criteria under global changes. This paper only provides an overview of technology hubs for possible implementation of various FEW systems, and the concept of associated costs-benefits-risks tradeoff. However, the selection of technology for optimal integration in a case-specific FEW nexus would largely depend on the geographic locations, availability and demand of resources, and the induced tradeoffs. In addition to the current technology hubs presented in this study (Part I), multilayer modeling platforms and multiagent decision-making processes are organized and elucidated in Part II as promising approaches for evaluating and benchmarking an urban FEW nexus at varying spatiotemporal scales to handle intertwined complexity from the perspectives of data, system, and society.

Information regarding existing and emerging technologies in this study might not be all-inclusive, and information about costs, benefits, and risks is oftentimes case-specific and an extension is required for more comprehensive applications. As research in this highly interdisciplinary area is progressively developing in this community, any innovation can trigger a more rigorous integration and synthesis. It is expected that these future extensive analyses for the optimal integration of technology hubs with their associated costs, benefits, and risks can stretch our preliminary insights in this paper for better integration and adaptation in the area of large-scale and complex urban FEW nexuses.

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ORCID

Ni-Bin Chang http://orcid.org/0000-0002-7162-7017
Qipeng P. Zheng http://orcid.org/0000-0002-4597-3426
Nassim Ait-Mouheb http://orcid.org/0000-0003-0099-0983

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Appendix A: List of technology codes used in this study

Technology code	Abbreviations
S1-PVS	Solar 1: Photovoltaic system
S2-CSP	Solar 2: Concentrated solar power
S3-SWH	Solar 3: Solar water heating
B1-BF	Bio-energy 1: Biofuels
B2-WP	Bio-energy 2: Biopower (wood pellets)
B3-BP	Bio-energy 3: Bioproduts
G1-EP	Geothermal 1: Electricity production
G2-DU	Geothermal 2: Direct use
G3-HP	Geothermal 3: Heat pump
T1-SG	Tidal 1: Stream generator
T2-TB	Tidal 2: Tidal barrage
T3-DTP	Tidal 3: Dynamic tidal power
T4-WtP	Tidal 5: Wave energy to power
W1-HA	Wind 1: Horizontal axis
W2-VA	Wind 2: Vertical axis
W3-DWT	Wind 3: Ducted wind turbines
ES1-SSB	Energy storage 1: Solid state batteries
ES2-FB	Energy storage 2: Flow batteries
ES3-FW	Energy storage 3: Flywheels
ES4-CAES	Energy storage 4: Compressed Air Energy Storage
ES5-T	Energy storage 5: Thermal
ES6-PH	Energy storage 6: Pumped Hydro-Power
ES7-H	Energy storage 7: Hybrid
SW1-RB	Stromwater 1: Retention basin
SW2-WDB	Stromwater 2: Wet detention basin
SW3-VNB	Stromwater 3: Vegetated natural buffers (VNBs)
SW4-B	Stromwater 4: Biofiltration systems
SW5-RI	Stromwater 5: Rainfall interceptor trees
SW6-ET	Stromwater 6: Exfiltration trench
SW7-TS	Stromwater 7: Treatment swales
SW8-PP	Stromwater 8: Pervious pavement
SW9-GR	Stromwater 9: Greenroof/cistern
SW10-NC	Stromwater 10: Natural area conservation
SW11-EL	Stromwater 11: Eco-friendly landscaping
WWT1-FWT	Water extraction and wastewater 1: Freshwater withdrawal technologies
WWT2-CT	Water extraction and wastewater 2: Centralized wastewater collection and treatment
WWT3-DT	Water extraction and wastewater 3: Decentralized wastewater treatment
WWT4-PW	Water extraction and wastewater 4: Potable water production
UA1-H	Urban agriculture 1: Hydroponics
UA2-A	Urban agriculture 2: Aeroponics
UA3-Aq	Urban agriculture 3: Aquaponics
UA4-V	Urban agriculture 4: Vericrop
UA5-MCS	Urban agriculture 5: Modular container system

(*continued*)

Continued.

Technology code	Abbreviations
UA6-CPS	Urban agriculture 6: Cubic production systems
UA7-WSNA	Urban agriculture 7: Wireless sensors network–aboveground (WSNA)
UA8-WSNB	Urban agriculture 8: Wireless sensors network–belowground (WSNU)
UA9-VRT	Urban agriculture 9: Variable rate technology
UA10-ASC	Urban agriculture 10: Automatic section control technology
UA11-SSVRI	Urban agriculture 11: Soil sensor and variable-rate irrigation
UA12-SDI	Urban agriculture 12: Subsurface drip irrigation
UA13-LO	Urban agriculture 13: Light optimization
UA14-RA	Urban agriculture 14: Rooftop agriculture
UA15-CG	Urban agriculture 15: Community garden
UA16-VF	Urban agriculture 16: Vertical farming (Sky farming)
UA17-PF	Urban agriculture 17: Peri-urban farm
UA18-IG	Urban agriculture 18: Industry greenhouse
UA19-IF	Urban agriculture 19: Indoor farming
EE1-CPG	Emerging energy 1: CO_2 plume geothermal power
EE2-ISGPG	Emerging energy 2: Integrated solar-geothermal power generation
EE3-HFC	Emerging energy 3: Hydrogen fuel cell
EE4-BPSC	Emerging energy 4: Bacteria-powered solar cell
EE5-MSTES	Emerging energy 5: Molecular solar thermal energy storage
EE6-TL	Emerging energy 6: Tidal lagoon
EE7-MSB	Emerging energy 7: Molten salt battery
EE8-LHH	Emerging energy 8: Low head hydro-turbine system
EE9-GS	Emerging energy 9: Gravity storage
ESW1-US	Emerging stormwater 1: Underground storage
ESW2-MAPS	Emerging stormwater 2: Managed aquatic plant system (MAPS)
ESW3-SH	Emerging stormwater 3: Stormwater harvesting
ESW4-DCIA	Emerging stormwater 4: Disconnecting directly connected impervious areas
ESW5-ATSAT	Emerging stormwater 5: Algal Turf Scrubber and anaerobic treatment
EUA1-BA	Emerging urban agriculture 1: Biofuel – algae
EUA2-PB	Emerging urban agriculture 2: Plant breeding – trait selection
EUA3-HES	Emerging urban agriculture 3: High efficiency sprayer
EUA4-HT	Emerging urban agriculture 4: Hydrogel technology
EUA5-GEM	Emerging urban agriculture 5: Green environmental media
CT1-PH	Centralized technologies 1: Pump and storage hydro-power system
CT2-WWT	Centralized technologies 2: Wastewater treatment
CT3-WDS	Centralized technologies 3: Water desalination
CT3-MIT	Centralized technologies 4: Municipal incineration
CT4-MLT	Centralized technologies 5: Municipal landfill