Integrative technology hubs for urban food-energy-water nexuses and cost-benefit-risk tradeoffs (II)

Design strategies for urban sustainability

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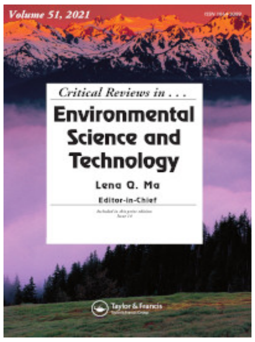

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Integrative technology hubs for urban food-energy-water nexuses and cost-benefit-risk tradeoffs (II): Design strategies for urban sustainability

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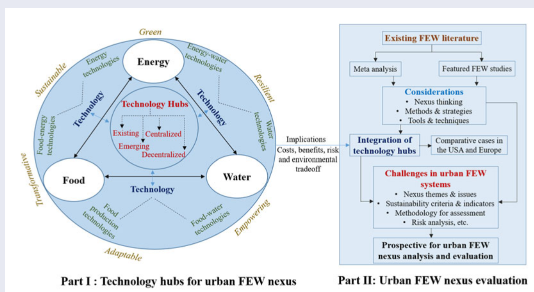
ABSTRACT

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



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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.

KEYWORDS Food-Energy-Water nexus; Technology hubs integration; Cost-benefit-risk tradeoff

1. Introduction

Globally, more than half of the population lives in urban areas that predominantly rely upon external supplies of food, energy, water, and other resources. Based on recent studies (OECD, 2012; UN, 2014b; Fabiola & Dalila, 2016), by 2050 the world's population is projected to grow to about 9.5 billion, with more than 70% of the world's population living in cities. This is anticipated to result in a 70% increase of total food demand between 2005 and 2050 (FAO, 2009), a 55% increase of total global water demand in 2050 as compared to 2000 (OECD, 2012), and a 30% increase of global primary energy demand in 2040 compared to 2017 levels (IEA, 2017). Intensive production and consumption of materials and goods alters land use and cover, biodiversity, and hydrosystems both locally and regionally, and the subsequent urban waste discharge impacts biogeochemical cycles and climate from the local to the global scale (Grimm et al., 2008). Consequences of rapid urbanization and increased resource demands in cities are further exacerbated by social factors related to poorly integrated resource management, changing managerial policies, land resources degradation, feedbacks of climate change, and economic fluctuations (Muller, 2007), and hence, to sustainable development (Zhang, Chen et al., 2018). The integrated management of these intertwined Food-Energy-Water (FEW) infrastructure systems is becoming increasingly important, as food, energy, and water sectors are strongly interconnected and interdependent, and the synergies among these three core infrastructure systems play a central role in sustainable development (Zhang, Chen et al., 2018; Grady et al., 2019). Different scales of FEW nexuses clustered across different communities are often considered complex large-scale systems with multidimensional, multidisciplinary, and multilayer natures.

The interlinkages among the FEW sectors are numerous, with multiple layers of interdependencies and interconnections associated with the available resources, internal cohesion among communities involved, and external climatic, geopolitical, demographic, and socioeconomic drivers. The governance structure of a FEW nexus is also an emerging key topic of discussion at all levels of government agencies due to its extraordinary importance. The current governance structure is oftentimes fragmental,

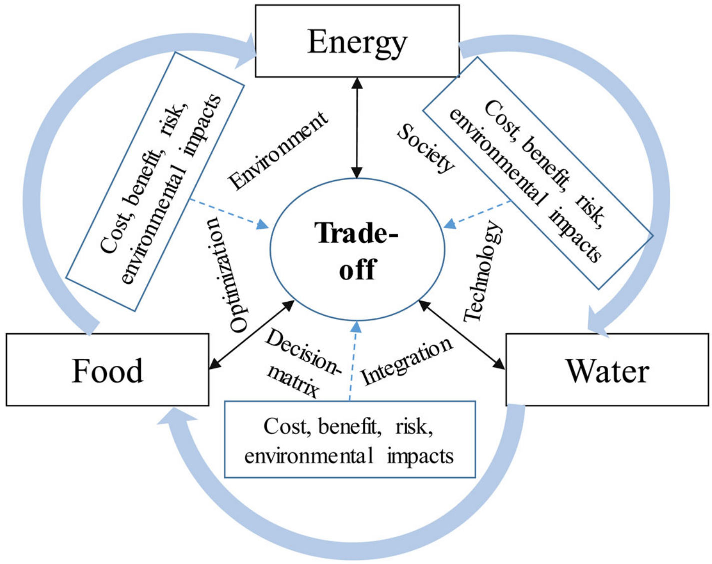

Figure 1. Theoretical framework of urban FEW nexus systems.

which may weaken the sustainable use of resources and the achievement of long-term food, water, and energy security (Rasul, 2016). For this reason, the consolidation of FEW nexuses at various scales is also related to an integrated decision-making process through which the relevant policy-makers and stakeholders must perform tradeoffs among their cost, benefit, and risk concerns (Kaddoura & Khatib, 2017; Kurian, 2017). The integrated philosophy of the theoretical framework of a FEW nexus is illustrated in Figure 1. Guidelines around a framework for the development of cross-sectoral policies are emerging, although they are not all-inclusive (Albrecht et al., 2018). These guidelines lead to the insurance of food and nutritional security, the creation of sound energy mixes, the effective supply of essential water resources, and the maintenance of environmental integrity.

According to Figure 1, interchanging flows of food, energy, and water in a FEW nexus play central roles in life support. Enhanced understanding of the complex interactions among multiple life support systems can lead to better strategies, policies, and technologies (Healy et al., 2015; Artioli et al., 2017; Dai et al., 2018). In recent years, fresh water supplies have become increasingly scarce and unpredictable as a result of extreme weather events such as long-term droughts and unexpected flooding, and large amounts of water are required in the production of agricultural crops and the generation of liquid fuel and electricity. According to the United Nations World Water Development Report, 69% of global freshwater withdrawals are consumed by agriculture crop production, and 75% of all industrial water withdrawals are committed to energy production (OECD, 2012; UN, 2014a,b; Fabiola & Dalila, 2016). On the other hand, about 30% of total global energy consumption is dedicated to food production and the associated supply chain (UN, 2014b). About 15% of water is used in the energy sector, and 18% of the total energy used globally is consumed by the water sector (Machell et al., 2015). The food supply chain can mobilize virtual water flows from water rich to water scarce regions, and can even help transport biofuel crops from fuel rich to fuel lean regions to provide sustenance in a renewed FEW nexus. Thus, reducing water and energy consumption becomes one of the most important prerequisites for sustainable development, as energy saving can lower the pressure on demands for water resources, and increasing efficiency in water use can reduce the amount of energy required for distribution, transport, and treatment of water (Dai et al., 2018). As a consequence, understanding the underlying processes and their sectorial interactions is critical for different FEW systems (Cai et al., 2018). Deepened insights via a system engineering approach can support sustainable resources management regionally and globally.

About a decade more ago, scientists began to notice the importance of the interdependence among the various individual eco-systems, and therefore began to dedicate more time and effort to nexus studies in terms of the systems engineering concept of "system of systems" such as a city within a megacity. For example, Scott et al. (2011) highlighted some fundamental water-energy coupling and relevant policy challenges, including the influence of physical and social dynamics of energy-water development on the wider demand of resources, and the impact of the water-energy nexus on global changes. These global changes include rapid urbanization, economic development and globalization, population growth, climate change, environmental externalities, and interlinked markets through globalization. In order to build and operate a successful FEW nexus under such a global change impact, it is important to closely consider both current and future opportunities in technological advancements, such as possible disruptive technologies in the renewable/alternative energy supply. Thus, critical thinking, research, and relevant policies are essential for triggering innovations among these interrelated sectors for seeking environmentally benign, cost-effective, forward-looking, and risk-informed sustainable solutions in support of sustainable development.

In recent years, an increasing academic effort has been directed to improve FEW nexus research and education in terms of nexus understanding, framework development, methods and indicators development, and governance and policy issues, in addition to some training programs. Although the FEW nexus proposes a promising conceptual framework, the philosophy for a successful transdisciplinary use of a FEW nexus and its associated engineering design strategies is still very limited (Walker et al., 2014; Albrecht et al., 2018). Such shortfalls have increased the need for systematically evaluating the interlinkages of food, energy, and water systems and/or the development of policies/culture-driven decision-making processes in different developing and developed countries. This effort will enable us to assess possible planning scenarios for further sustainable development in different types of cities, from small, to medium, to megacity scale based on sustainability criteria. Therefore, this study presents a comprehensive review by analyzing the contemporary issues related to different FEW nexuses with multiple spatiotemporal scales.

As a companion study to Part I, this review article aims to generate several contributions to the FEW nexus research community by: 1) illustrating the existing FEW nexus focus and coverage, 2) analyzing the challenges of FEW nexus research based on the selected critical literature, 3) providing some typical examples for the integration of technology hubs in different FEW systems with case-based engineering studies, 4) summarizing the challenges of implementing effective FEW nexuses, and 5) creating a multilayer managerial framework for urban FEW nexuses to address the challenges highlighted in this comprehensive review.

2. Methodology: Meta-analysis of FEW Nexus literature

In this paper, a comprehensive meta-analysis is conducted for a systematic review based on well-established literature databases, such as Web of Science and Scopus, with relevant key words, including *nexus*, *water-food-energy nexus*, *water-energy nexus*, *water-food nexus*, *nexus technology*, *nexus methods*, *nexus tools*, *nexus criteria*, *urban water-energy-energy nexus*, *urban nexus*, *nexus sustainability*, *nexus indicators*, *nexus policy*, *optimization*, *climate-related nexus*, etc. Within this survey, we focused on peer-reviewed journal articles. About 100 papers were selected for further analysis, and more than 87% of these selected papers were published after 2017. The analyzed literature, with the names of authors, titles, and journals, are summarized in Supplementary Information (S-Table 1). Due to the nature of the research, these journal articles were published by a wide range of journals, covering resource management, science, engineering and technology, modeling, computational analysis, policy and public administration, sustainable development, urban development, etc. (Figures 2 and 3), highlighting the interdisciplinary research endeavor of various types of FEW systems.

The selected papers were then screened and classified according to the predefined 10 criteria, including the study location; type of study; type of nexus; approach of analysis; methodology and tools adopted; type of data, including the sources; scale of nexus analysis; nexus highlights, etc. The criteria can provide significant insights for identifying trends and topics

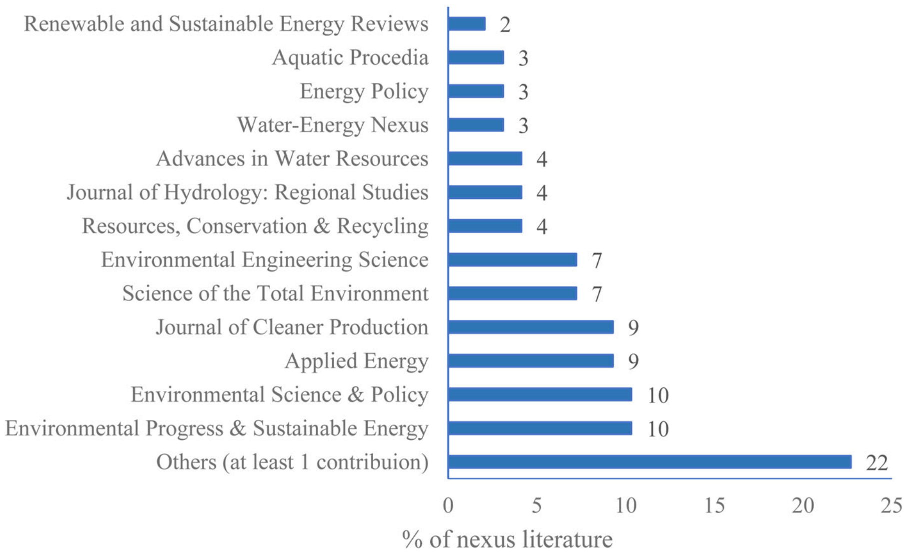

Figure 2. Selected nexus research published in scientific journals.

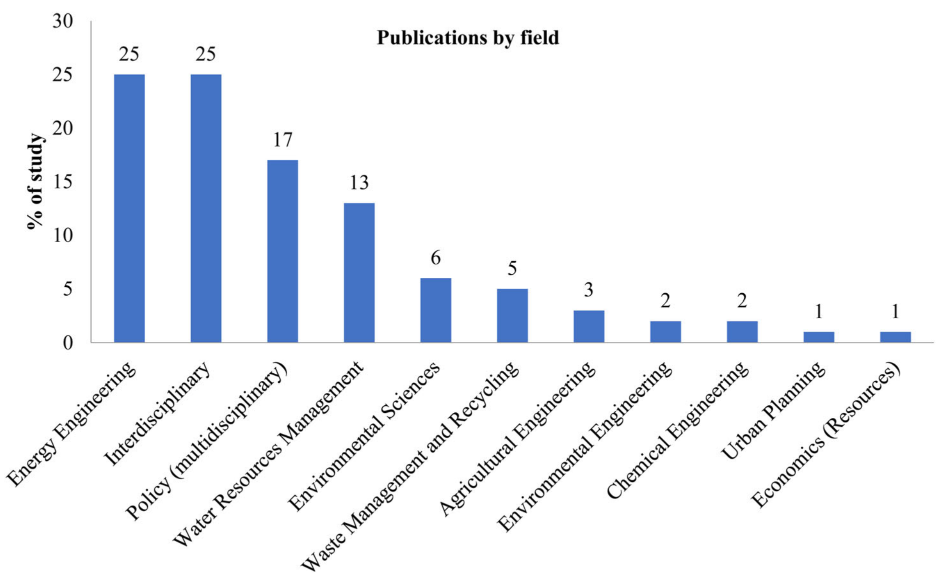

Figure 3. Nexus related publications by field.

regarding existing nexuses. It may lead to improved understanding of the focal point of nexus research based on the temporal and spatial contexts. The selected papers were then analyzed in-depth according to the variation of nexus considerations, nexus issues, indicators chosen, technology adopted, feasibility and challenges, etc., with respect to 12 case-specific comprehensive studies. In addition, several popular methods and tools were critically analyzed according to scope, externalities, level of

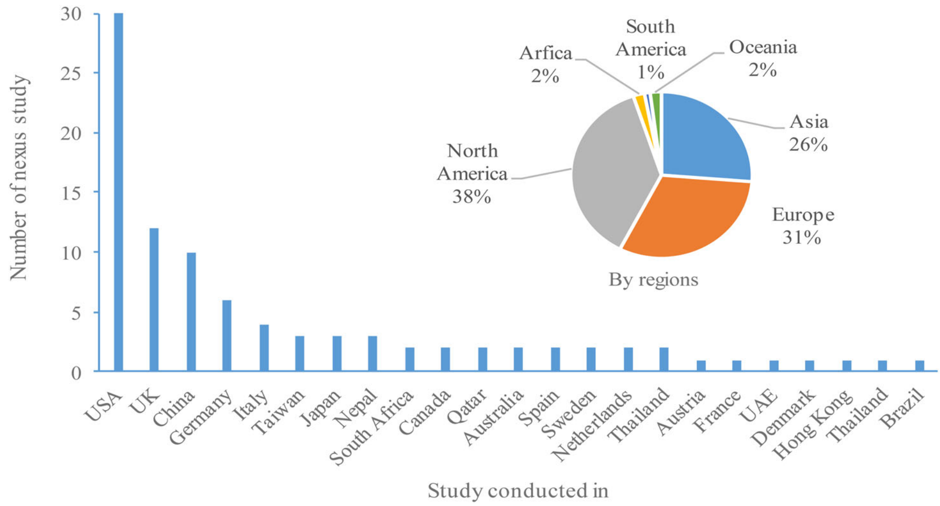

Figure 4. Geographical representation of selected research regarding the FEW nexus.

integration, and limitations in different case studies. Three case specific implementations of FEW initiatives, along with the integration of potential FEW technology hubs across USA and Europe, were discussed as a demonstration and typical examples in practices. Based on the outcomes, an integrated nexus assessment model is proposed for comprehensive urban sustainability assessment in the context of sustainable urban systems.

3. Results and discussion

3.1. Featured analysis of the FEW Nexus literature

The global research of the FEW nexus based on the selected literature is shown in Figure 4. The highest representation is from the USA (35%), and then the UK, and China, respectively. North America (mainly USA) and Europe lead the world, accounting for about 69% of the nexus related research publications together, while publications from Asia, Oceania, Africa, and South America accounted for about 26%, 2%, 2%, and 1%, respectively.

These papers can be categorized from three different perspectives to understand the goals and trends. In terms of article type, about 43% were case-specific and mainly focused on different nexus applications in particular geographic locations (Wang et al., 2017; Chen et al., 2018; Uddameri & Reible, 2018; Campana et al., 2018; Hailemariam et al., 2019). Approximately 34% of nexus studies were based primarily on the analysis of conceptual frameworks, understanding of nexus and nexus developments, policy and governance, risks and opportunities, synergies and tradeoffs, nexus research opportunities, and so on (Romero-Lankao et al., 2018;

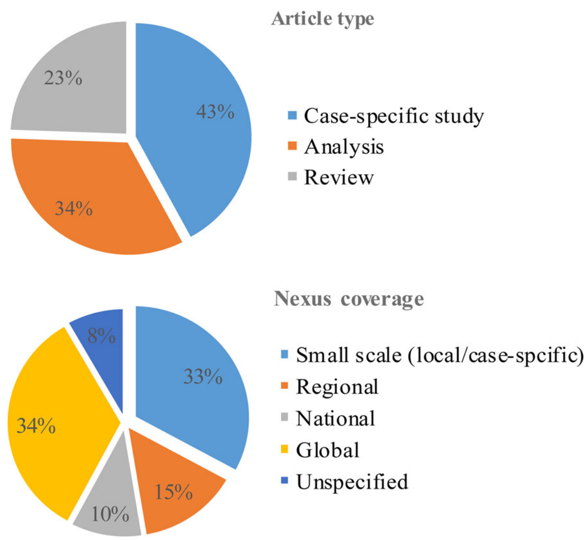

Figure 5. Type of study with FEW nexus related research.

Fader et al., 2018; Bergendahl et al., 2018). The remaining 23% of studies focused on current nexus structure, developments, integration, methods and tools, etc., by synthesizing existing nexus-related studies (Al-Saidi & Elagib, 2017; D'Odorico et al., 2018; Mannan et al., 2018). In terms of spatial scales, about 34% of the nexus studies were of global scale (mostly analysis and review papers), while 15% were regional (both analysis and case-specific applications), 10% were national scale (similar to regional), and 33% were case-specific studies with local implications (Figure 5).

A more comprehensive illustration of existing nexus research is shown in Figure 6, in which black lines represent a focus on the study of a particular resource (e.g., food, energy, or water), yellow lines indicate the study of integrated systems with two principal resources, and gray dashed lines emphasize the interlinkages of subsections of different nexuses. In terms of focus and level of integration, 29 papers focused on the FEW nexus, but these mostly aimed to conduct general analysis and systematic review, whereas 10 papers focused on water (Larsen & Drews, 2019; Rosa & D'Odorico, 2019), 5 on food (Abdelkader et al., 2018; Neto et al., 2018; Zhang, Campana et al., 2018), 4 on energy (Yuan et al., 2018; Ahjum et al., 2018; Whitney et al., 2019), 9 on water-energy nexus (Engström et al., 2017; Wang et al., 2017; Wang et al., 2019; Liu et al., 2019), 2 on energy-food (Hanes et al., 2018), and 1 on water-food (Zhang & Vesselinov, 2017). The rest of the articles applied nexus research from various angles. They include, but are not limited to, agricultural drought management (Campana et al., 2018), bio-fuels (Moioli et al., 2018), governance and policy (Rasul & Sharma, 2016; Artioli et al., 2017; Pahl-Wostl, 2019; Märker et al., 2018), waste and wastewater (Wang et al., 2018), climate vulnerability

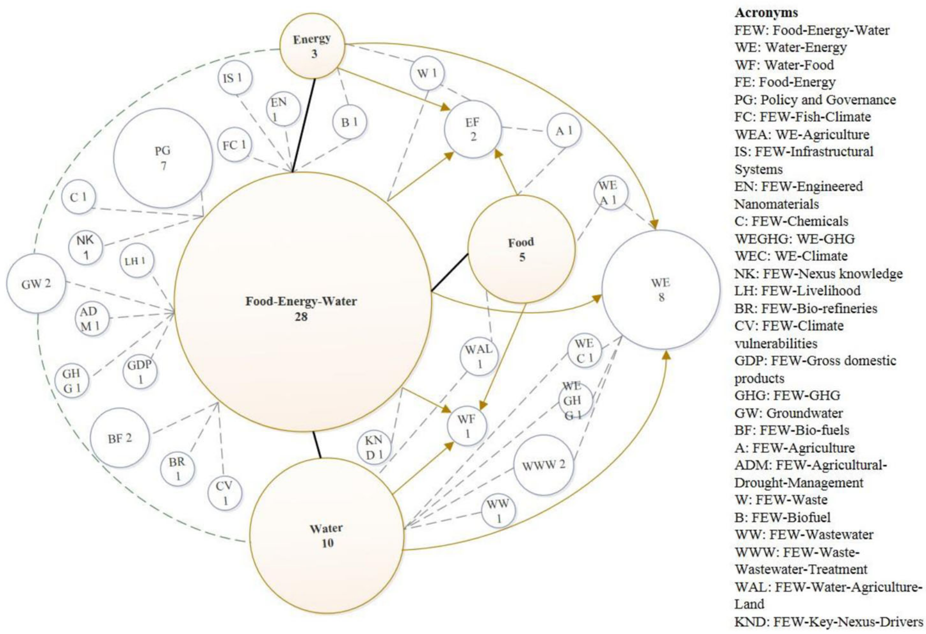

Figure 6. Nexus focus and integration.

(Howarth & Monasterolo, 2017), projecting paths to FEW nexus sustainability through ontology (Babaie et al., 2019), linking food-water systems for enhancing child health in developing regions (Oerther et al., 2019), and nexus knowledge and understanding (Howarth & Monasterolo, 2016; Martinez et al., 2018) under different nexus systems. However, the comprehensive case-based practical application of an interconnected and interdependent FEW nexus with the adoption of existing and emerging technologies for a particular region is still limited (e.g., White et al., 2018).

3.2. Methodological considerations in the existing Nexus research

3.2.1. Nexus thinking

The FEW nexus approach is defined as an approach that integrates resource management systems and governance at various scales across the three different sectors. This approach is designed to reduce the negative surplus and enhance the efficiency of resources consumption via integrated planning and management toward sustainable development goals (Liu et al., 2018). Although the effective implementation of the nexus approach is still in its infancy, different approaches have been proposed and used to enhance the knowledge of FEW systems in different spatiotemporal scales and forms, and evaluate possible tradeoffs related to synergies among the three key resource systems. Some specific examples are provided herein to analyze how a FEW nexus approach is adopted from different perspectives in the existing literature. The scale could be as small as a local community or as large as the globe, which requires using gross domestic product (GDP) as an economic indicator.

For example, Smajgl et al. (2016) proposed a dynamic framework for a FEW nexus in the Mekong region, where the Delphi technique was used to promote the learning of nexus interactions to decision-makers. Rasul (2016) provided a holistic nexus framework in Southeast Asia by integrating policies and strategies in the three resource sectors. Strengthening cross-sectoral coordination, harmonizing public policies, aligning cross-sectoral strategies including incentive structures, strengthening regulation, and facilitating smart investment in nexus technologies were the main elements highlighted in the framework. For improving operationalization and decision-making processes, de Vito et al. (2017) proposed an index-based approach including the irrigation-water footprint, the energy footprint for irrigation, and irrigation water-cost footprint indexes for sustainability assessment of irrigation practices. Very recently, by using system dynamic models with a Monte-Carlo simulation scheme, Sušnik (2018) analyzed the FEW-GDP system globally and found that GDP is more deeply correlated to electricity consumption and water withdrawals than food production, but strong causal influence was found in food-GDP sectors based on the causal analysis. In addition, Hussien et al. (2017) and Hussien et al. (2018) used a bottom-up approach with a case study to model the FEW nexus. By reviewing recent studies, Tian et al. (2018) proposed an integrated FEW nexus model that coupled ecosystem and economic considerations with a regional climate model to understand the interactions of the ecosystem–human–climate systems that can be quantitatively evaluated and used as sustainability indicators of the agricultural system. An online open access simulation and visualization tool was proposed by Xue et al. (2018) to analyze different circular economy scenarios associated with their respective FEW nexuses. The tool can display the impacts of FEW policies and technologies both qualitatively and quantitatively, including different indicators of social, economic, and environmental aspects. The tool is a good initiative for understanding the local FEW nexus with an emphasis on circular economy. However, Vakilifard et al. (2018) pointed out that the development of optimization models for capturing spatial aspects and environmental indicators and impacts is the main challenge for the frameworks and strategies of the existing nexus literature. The study also highlighted that models are limited in current nexus research in that they only consider uncertainties associated with the future water demand and renewable energy supply. All the highlighted literature exhibits the potential for the inclusion of the further development of a nexus approach in terms of methodology development, scales of nexus, and different considerations including the selection of indicators, etc.

3.2.2. Methods and strategies

This section provides an overview of different methods and strategies used in nexus research. In existing nexus studies, several useful methods were adopted for analyzing and correlating different nexus backgrounds. The common methods include mathematical modeling (Kenway et al., 2011; Wang et al., 2017; Xie et al., 2018), life cycle assessment (LCA) (Meldrum et al., 2013; Wang et al., 2018; Bozeman et al., 2019), network modeling (Zimmerman et al., 2018), agent-based modeling (Bieber et al., 2018), spreadsheet models using numerical equations (Wilkinson, 2000), surveys with factor analysis (Bullock & Bowman, 2018), system dynamics model (Hussien et al., 2017), and geographic information system (GIS) (Gurdak et al., 2017; Uddameri & Reible, 2018). Among them, LCA is becoming a popular method (Wang & Zimmerman, 2011; Mannan et al., 2018), as LCA considers both direct and indirect inputs and outputs of resources (Retamal et al., 2008; Wang et al., 2018). Forecasting models were used in studying climate variability and energy and water consumption (Hoffman, 2010; Ali, 2018; Chen et al., 2018). Visual display tools, including GIS (Uddameri & Reible, 2018), Sankey diagrams (Chen et al., 2018), and system dynamics (Hussien et al., 2018) were also used to understand resource production, distribution, and consumption. In addition, qualitative methods were utilized to analyze the governance and policy of a nexus to facilitate the decision-making process and public awareness (Artioli et al., 2017; Bullock & Bowman, 2018). So far, most of the methods were used for a specific sectoral analysis, either in water or energy (Dai et al., 2018; Yoon, 2018). In addition, some of the common methods and tools used, data required, their implications, and associated challenges in practical case-specific studies are shown in Tables 1 and 2. An emerging trend is coupling models from different disciplines and communities (e.g., earth system model, agent-based model, and system dynamics model) that represent the social-ecological-infrastructural systems for better quantifying and characterizing urban FEW systems.

3.2.3. Tools and techniques

This section explicitly analyzes different tools and techniques used in existing literature for evaluating different FEW systems. Previous reviews have explored some of the important nexus assessment tools, including the Water, Energy, Nexus Tool 2.0; Energy intensity; Multi-Regional Input – Output analysis model; Multi-Scale Integrated Assessment of

Table 1. Methods and tools used in existing nexus research.

Name of method	Tools	Example of study	Scope of tools/Strength	Externalities	Integration	Limitations
Input-Output (IO) modeling including Multi-Regional IO (MRIO)	Genetic algorithm	Wang et al. (2017), Chen et al. (2018), Fang and Chen (2017), Ahjum et al. (2018)	Recognize the sectors and pathways for urban water-energy nexus management system; resource use, i.e. water consumption, and agricultural production based on the global supply chain using MRIO modeling; regional water-energy demands.	Provides an overview of a particular nexus system for a specific location. Can be adopted in regional, national, and global applications.	Water and energy demand and consumption. Farming land and freshwater use in the global supply chain.	Difficulties in data accessibility and granularity. The model can provide a general feature of a region rather than a sector specific nexus analysis. Very high uncertainty is associated with the data and other factors. Lack of comprehensive assessment using multiple variables for multiple resources.
Fuzzy optimization	Mathematical programing	Zhang and Vesselinov (2016)	An interactive fuzzy optimization approach was used to model the water-energy nexus problem computationally by involving bi-level decision making.	Addressed the challenges of decision-making in energy-water nexus management. Cost-effective and optimal decision-supports that enhanced the understanding of energy-water linkages.	Electricity generation, fuel supply, water supply (including groundwater, surface water, and recycled water), capacity expansion of power plants, and GHG emission.	The optimization model was adopted to handle the hypothetical energy-water problem. Specifically focused on a regional/ national level problem The model does not cover uncertainty analysis. Capable of optimizing only a few indicators.
FEW nexus Optimization model	Genetic algorithm	Zhang and Vesselinov (2017), Uen et al. (2018)	Simplified framework for optimization of FEW nexus management system; multi-objective reservoir optimization.	Can be used to provide cost-effective decisions for optimal WEF management. Flexible model structure. Applicable from local to national scale if necessary data are available.	Energy supply, electricity generation, water supply-demand, and food production and their associated costs, GHG emissions. Water supply, irrigation.	Hypothetical model. Excluded multiple components including the policy issue. Limited factors and variables are integrated. Very high uncertainty is associated with the model due to changes of variables (e.g. costs) temporarily and spatially.
Life cycle assessment (LCA)	SimaPro; Genetic algorithm	Das and Cabezas (2018), Yuan et al. (2018), White et al. (2018), Salmoral and Yan (2018), Al-Ansari et al. (2017)	Different applications including water and energy requirements for food consumption, waste-to-energy and other renewable technologies for food production; regional FEW systems with environmental impacts evaluation; regional bioenergy production systems, etc.	Scenario analysis. Wide-range of environmental indicators. Facilitates policy decision. Local/case-specific, national/ regional, and global scale applications. Sensitivity analysis and system optimization.	Quantifies material flows, natural resources, and energy consumption. Upstream virtual water including embodied energy in food consumption. Water, energy, farming land use, water scarcity, and GHG and SOx emissions.	Data acquisition (both background and foreground) is the main difficulty for LCA modeling. Limited comprehensive LCA applications in FEW nexus (except a few case-specific with limited variables).

Life cycle sustainability assessment (LCSA)	Mixed-integer linear programing	Wang et al. (2018)	Integrated several types of waste to energy pathways in a city scale.	Integrated with life cycle environmental assessment (LCA), life cycle costing (LCC), and life cycle social assessment (S-LCA). For optimization, mixed-integer linear programing was used.	Wastewater, municipal solid waste, and agriculture waste to electricity generation.	Only electricity was considered as the representative energy product Case-specific model with a limited set of variables. Excluded clean energy technologies and other energy policies. Very limited LCSA indicators were adopted, this may be due to the lack of comprehensive LCI data.
Nexus Index	Mathematical modeling	Moioli et al. (2018)	Sustainability of bioenergy production under FEW nexus perspectives.	Bio-fuel production on the water use, land consumption, and food availability. Simulates the resource use efficiency nationally. Potential for dynamic efficiency study.	Nexus index including the use of three resources (water, food and land) for the final output (energy). Crop yield, land use, bio-fuel production, and water consumption	Limited number of variables are included. Multiple variables (e.g. crop yields) and resource efficiency need to be further studied. Further attention has to be paid to technological changes on the resource use.
GIS and remote sensing	ArcGIS; Satellite image processing	Gurdak et al. (2017), Zhang, Campana et al. (2018), Campana et al. (2018), Uddameri and Reible (2018)	Agricultural drought management using spatial agriculture and water system modeling; water and groundwater vulnerability model.	Can provide real-time guidelines for a comprehensive drought management system. Applicable to precision agriculture and crop yield forecast for using high-resolution satellite data. Can be used in optimization of agriculture and energy systems.	Requires crop water demand, water availability, electricity and crop yield for irrigation. Water quality parameters.	High-level of expertise is required to implement such a model due to different data handling and complex modeling systems. Due to the complexity of data, only a limited number of variables can be included.
Predictive model	Sensing system (sensor)	Mickelson and Tsvankin (2018)	Generate real time data for predictive models of FEW systems.	High level predictive model of FEW systems.	Sensing data was used to predict the dynamic behavior of the water supply system.	Applicable to local/case-specific FEW systems only. Multiple sensors and a high level of expertise is needed for such an application, especially for multi-sensing data acquisition. System failure may be another limiting factor.
Index-based approach	Mathematical modeling; CropWat® software	de Vito et al. (2017)	Sustainability evaluation for irrigation practice based on FEW nexus.	Multi-dimensional implications of irrigation practices. Quantitative evaluation of the sustainability for irrigated agriculture.	Irrigation-water footprint, energy footprint for irrigation, and irrigation water-cost footprint indexes.	Indexes were proposed mainly based on a few footprints. Provides a relative sustainable assessment based on these three indexes. The approach operationalizes FEW at the local scale.

(continued)

Table 1. Continued.

Name of method	Tools	Example of study	Scope of tools/Strength	Externalities	Integration	Limitations
Participatory modeling approach	System dynamic model; fuzzy cognitive mapping	Martinez et al. (2018); Howarth and Monasterolo (2016)	Understanding the key nexus drivers; awareness and building consensus for the FEW nexus between the different stakeholders.	Graphical representation of causal relationships among variables in a system. Scenario simulation. Facilitates policy decision.	Knowledge share and stakeholder's involvement for FEW nexus understanding and policy integration.	Enables systems modeling with limited data. Absence of temporal dimension. Direct involvement of stakeholders is needed.
System dynamic modeling (SDM)	Monte-Carlo simulation; Regression; Stella Architect; Vensim® PLE software	Sušnik (2018), Abdelkader et al. (2018), Xue et al. (2018), Hussien et al. (2018)	SDM are used to analyze the interconnected systems of resources with various factors, but highly complex for creating new scenarios.	Scenario simulation. Local/case-specific, national/ regional and global scale applications. Possible to perform sensitivity simulations and system optimization. Decent visualization of complex systems.	GDP to national water withdrawal, food production, and electricity consumption. Sustainable water supply by highlighting seasonal variations. Water-energy policy nexus.	Technological developments/ changes were not considered that may significantly affect FEW systems. Comprehensive FEW nexus evaluation for multiple resources with complex indicators using SDM is still lacking.
Agent-based modeling (ABM)	Mixed-integer linear optimization model	Bieber et al. (2018)	By using ABM, resource demands were simulated and predicted based on spatial and temporal scales by including several factors such as capital expenditures and operational costs, environmental impacts, and the opportunity cost of food production.	Incorporated capital expenditures, operational costs, CO_2 emission and the opportunity cost of food production. Scenario analysis.	Used mixed-integer linear optimization based on the resource-technology. Network. Estimation of water and electric power use characteristics for each agent type on discrete time intervals.	Multiple datasets including the demographic and socio-economic data are required. Final food processing and packaging was not considered. Limited optimization factors were considered. Bias and preconceptions about causal relationships possible.

Table 2. Cost-benefit risk-tradeoffs with respect to sustainable indicators for metropolitan regions.

FEW System	FEW Sector	Cost	Benefits	Risks
Miami	Food (drip irrigation and hydroponics)	High investment and operation costs	Mitigation of water utilization High efficiency and local food production Minimal energy demand Controlled cultivation environment for optimization of crop production Appropriate for rooftop agriculture Reduce urban heat island effect Hydroponics employs recycled gray water or stormwater	Sometimes difficulty in monitoring irrigation Difficulties in design, maintenance and operation High energy demand from hydroponic system
	Energy (Solar PV and anaerobic digestion)	High installation cost for PV Construction costs for anaerobic digester	Reduction of GHG emissions and carbon footprint Production of methane and hydrogen from digester Decrease energy demand from utility grid increasing community resilience Low O&M costs Anaerobic digestor can also be integrated for wastewater treatment	PV has low energy production efficiency Can have large ecosystem footprint
	Water (Stormwater/LID)	Minimal treatment costs	Reduction of water footprint and lessen stress on surface water and groundwater sources for non-potable uses Reuse and recycle of stormwater Low cost LID technologies	May need prior treatment (nutrients)
Amsterdam	Food (Green roof)	Low installation costs	Reduction of urban heat island effect and cooling load Appropriate for rooftop agriculture Employ stormwater for irrigation Stormwater runoff reduction Carbon sequestration and decrease in carbon footprint Decrease of ecosystem footprint Nutrient recycling Integrated with other urban farming technologies	Constant maintenance and laborious Crop growth competition
	Energy (Biofuel, Biopower and Bioproducts)	High investment costs Requires capture and storage units Material transportation costs for biopower	Reduction of GHG emissions and carbon footprint Use waste and recycled materials Biodegradable and nontoxic biodiesel Production of alternate transportation fuel High energy content in biopower from dry wood Bioproducts decrease use of petroleum-based products Bioproducts are biodegradable and sustainable	Can have large ecosystem footprint (deforestation, exploitation) Encourages competition with food crops Shortage in supply of raw material Large water footprint Low energy output (biofuel) Production of air pollution

(*continued*)

Table 2. Continued.

FEW System	FEW Sector	Cost	Benefits	Risks
	Water (Stormwater) SW1-RB	Minimal treatment costs	Reduction of water footprint and lessen stress on surface water and groundwater sources for non-potable uses Reuse and recycle of stormwater Low cost LID technologies	May need prior treatment (nutrients)
Marseille	Food (WWTP to fertilizer production)	Reduce O&M costs of WWTP Less expensive fertilizer option	Nutrient recycling Application for crop production in urban farming technologies Minimization of ecosystem footprint by reducing exploitation of fertilizer raw materials Reduction of wastewater biosolids Often already produced in wastewater treatment process (e.g. struvite)	Possible reduction of crop production use of sewage sludge as fertilizer Contamination of land and water
	Energy (Biofuel, Biopower and Bioproducts)	High investment costs Requires capture and storage units Material transportation costs for biopower	Reduction of GHG emissions and carbon footprint Use waste and recycled materials Biodegradable and nontoxic biodiesel Production of alternate transportation fuel High energy content in biopower from dry wood Bioproducts decrease use of petroleum-based products Bioproducts are biodegradable and sustainable	Can have large ecosystem footprint (deforestation, exploitation) Encourages competition with food crops Shortage in supply of raw material Large water footprint Low energy output (biofuel) Production of air pollution
	Water (Wastewater) WWT2-CT/ WWT3-DT	Operation costs primarily energy Decentralized wastewater treatment has low capital, O&M, and treatment costs than centralized	Utilization of biosolids for biogas production Reduction of ecosystem footprint from composite centralized design Minimum energy consumption in decentralized system Reduction of GHG and carbon footprint Reclaimed water used for irrigation or aquifer recharge	Large ecosystem footprint for decentralized system (lagoons) Overflow during rain events Water pollution from bad operation

Society and Ecosystem Metabolism; The Global Change Assessment Model in the USA; Water Evaluation and Planning system and Long Range Energy Alternatives Planning; Platform for Regional Integrated Modeling and Analysis; Water Analysis Tool for Energy Resources; Multi-Regional Nexus Network; Water-Energy Sustainability Tool Web; FAO Nexus Assessment Methodology; WBCSD Nexus Tool, and the Water, Energy and Food Security Nexus Optimization Model (Kaddoura & Khatib, 2017; Dai et al., 2018).

However, the tools above have rarely been adopted in recent case-specific nexus studies, with the exception of the input-output analysis and mathematical programing. Tools adopted (in respect to their methods) in some of the case-specific nexus studies are summarized in Tables 1 and 2. For example, Yuan et al. (2018) analyzed bioenergy production rates and compared the advantages of bioenergy to the existing policy on renewable energy in Taiwan through an integrated LCA, linear programing, and climate change simulation model under the nexus paradigm. The study found that electricity generation using biofuel (e.g., bio-coal) produced from rice straw is environmentally sustainable. In addition, Kumazawa et al. (2017) proposed a knowledge sharing and collaboration tool for interdisciplinary research based on an ontology engineering approach, which is a type of semantic web technology that offers common terms, concepts, and semantics. Ahjum et al. (2018) conducted a case study of a water-for-energy development nexus based on the South African national energy-economic system model. The model is a non-spatial national representation of energy goods, service flows, and energy technologies with associated costs and emissions. Based on the modeling of water-for-energy for a specific region, the study concluded that energy supply choice is influenced by several factors, such as water cost, quality, etc.; the integrated water supply network is more climate resilient, and there's a risk for stranded water supply infrastructure. However, the model is mainly focused on power generation, despite highlighting the need for water for food, environmental extremes, political influences, technology changes, national/regional attributions, etc. Thus, more factors need to be integrated and analyzed in the FEW nexus system for sustainable development.

3.3. Integration of technology hubs for FEW systems – Comparative case studies

This section provides three examples of the integration of technology hubs into different coastal FEW systems in cultural contexts worldwide, including Miami, Florida in the United States, Amsterdam in the Netherlands, and Marseille in France.

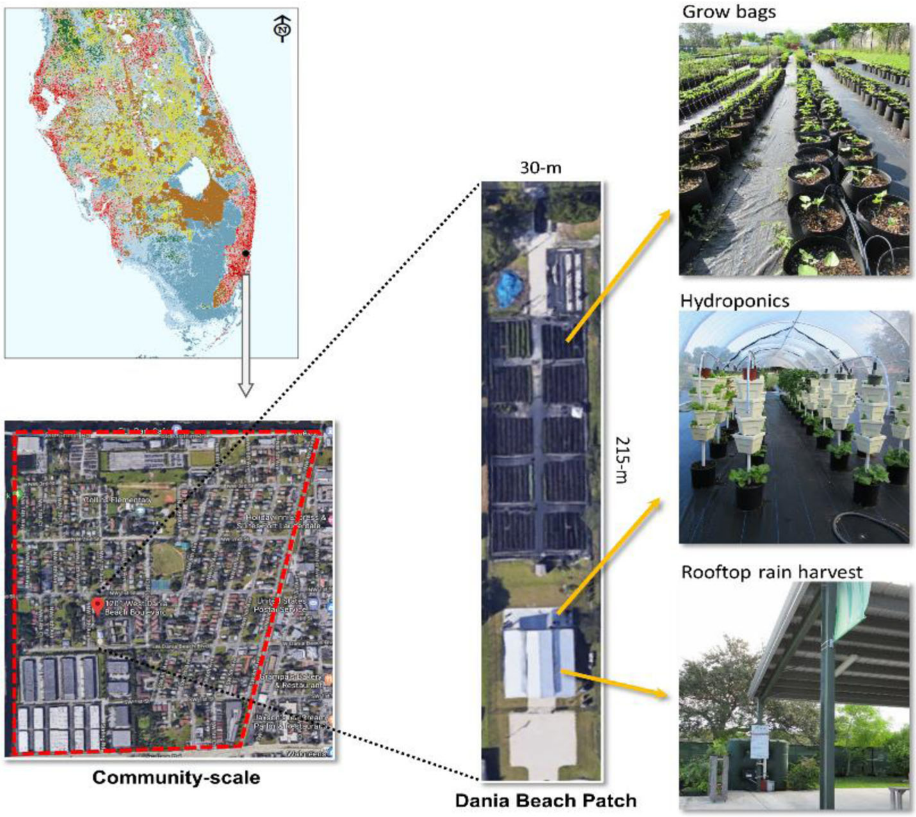

Figure 7. Study region of Dania Beach Patch, its geographic location (upper left), community scale at which it is located and serving (lower left), spatial extent (middle), and illustrations of existing on-site practices such as grow bags, hydroponics, and rooftop rainwater harvesting.

3.3.1. FEW systems in Dania Beach, Miami, Florida

3.3.1.1. Study region. Miami, located in South Florida, is an economic, financial, and cultural hub, and one of the most attractive tourist destinations in the world. The Greater Miami Area covers an area of about 15,890 km^2, the 4^{th}-largest urban area in the US, and had a population of more than 6 million in 2017. The city of Miami is the center of the Greater Miami Area, promoting economic development, entertainment and media, and international trade, and is considered the largest urban economy in Florida and the 12th largest in the US (MMA, 2019), with a continuously expanding population.

Our study was conducted at the community scale and focused on the Dania Beach Patch (DBP) – one of the exemplary urban community gardens and leading initiatives of urban farming in south Florida, USA (Figure 7). DBP occupies ∼6,475 m^2, measuring 30-m from east-west, and 21.5-m from north-south (1.7 acre of land), and is located in and primarily serves a low-income community (∼1,000 households) classified as a 'food desert' by the US Department of Agriculture (USDA). According to the

USDA, about 13.5 million people in these census tracts have low access to sources of healthful food; this area is therefore designated as a food desert with a need for improvement of food security.

3.3.1.2. Social-environmental benefits. DBP was converted from a dumpsite and initially sponsored through a suite of collaborative efforts among the City of Dania Beach, the Dania Beach Community Redevelopment Agency, and the Broward Regional Health Planning Council. It was originally developed to eliminate urban blight, improve quality of life by providing green spaces in highly impervious urban residential districts, and provide community access to locally grown, fresh food. Another major goal of DBP is to enhance food nutrition and facilitate connections between all residents of the community. DBP also provides trainings throughout the community (e.g., urban growers, residents) on sustainable urban agriculture management and practices, as well as temporary employment and volunteer opportunities. It is dedicated to promoting healthy living through different educational and outreach activities, which have been held regularly and made accessible to residents, students, and regional schools. Since its emergence in 2012, through support from various local and federal agencies and private foundations, it has evolved into one of the largest community gardens in Broward County. DBP has also established a local farmers' market that provides a variety of affordable and fresh vegetables to the community residents. With recent support from the USDA, DBP is now launching a number of "mobile farmers' markets" to expand its reach to the adjoining neighborhoods, with particular focus on meeting the food demands of low-income communities and thus better addressing food insecurity.

3.3.1.3. Current status and existing technologies. Due to the infertile Myakka soils (primary comprised of rock known as Miami limestone, sand, marl, and muck), a high water table, and susceptibility to saltwater intrusion and sea level rise, "grow bags" (Figure 7) are the main approach for production, in which crops are cultivated in a contained bag of good-quality soils. More recently, other production methods such as hydroponics and vertical farming have been increasingly adopted to improve productivity. Major products from DBP are seasonal roots and green vegetables, with a current onsite production capacity of ~4,990 kg (~11,000 pounds). With its focus on environmental sustainability, a number of technologies have already been incorporated to enhance water and energy use efficiency, such as dripping irrigation, solar panel powered hydroponics systems, and rain barrels for stormwater reclamation.

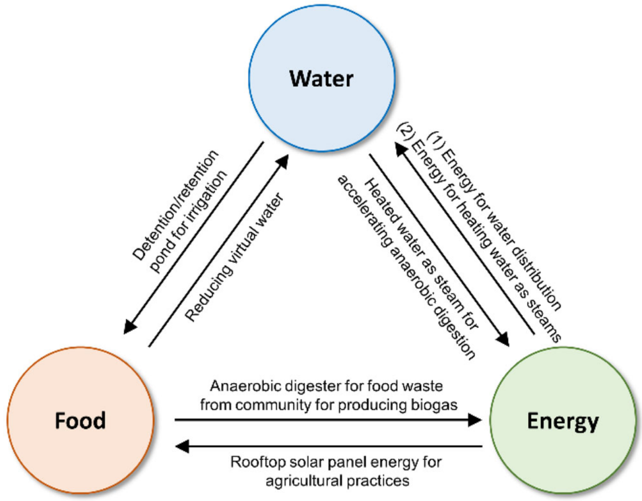

Figure 8. Conceptual diagram demonstrating the interdependencies and interconnections in the FEW nexus at the community scale in Miami, USA.

3.3.1.4. Integrative technology hubs. In this study, we proposed the integration of four types of FEW technologies that are both feasible and desirable based on initial feedback from operating managers and key actors of DBP. These include: 1) green energy from photovoltaic systems installed on all the roofs on the property (including a ~500 m^2 pavilion and several small buildings); 2) onsite anaerobic digestion for biogas production; 3) point-based low impact development in the form of retention/detention pond and rainwater harvesting/storage facilities; and 4) large-scale adoption of urban farming technologies, including dripping irrigation and hydroponics systems. These proposed integrative options, along with existing technologies, can be grouped to earn important opportunities for the realization of the interconnection and interdependencies of the FEW nexus at the community scale (Figure 8). Specifically, green energy generated from PV systems can be used for supporting agriculture production ("energy for food"), as well as for water distribution and heating water as steam ("energy for water"). Water steams can also be used to accelerate the anaerobic digestion process for the production of biogas ("food for energy") as an alternative energy source ("water for energy"). Water harvested from rain barrels or stored in the detention/retention ponds can be used for irrigation ("water for food") and, in turn, advanced irrigation technologies can help enhance water use efficiency and reduce overall water use ("food for water"). Another "food for water" pathway involves the declines in virtual water flows associated with food imports as a result of local food production to offset external food demands.

In this community-scale FEW system in Miami, the potential costs, benefits, and risks of associated technologies (highlighted in Sections 3.1-3.2 of

Part I) have to be critically evaluated with suitable planning scenarios, culture-oriented thinking, and site-specific characteristics in the future. Moreover, sustainability assessment of a nexus with such technologies should be evaluated in terms of water, carbon, and ecosystem footprints. The metrics for sustainability assessment may be structured by means of a suite of separate modeling efforts. As mentioned, the sustainable indicators of water, carbon, and ecosystem footprints can be assessed to determine the cost, benefits, and risks related to the application of the four types of FEW technologies in DBP. These indicators, which vary for each FEW sector, can be ultimately evaluated in terms of tradeoffs after the performance of cost-benefit-risk optimization to yield the most favorable option in terms of sustainability, cost and risk minimization, and reduction of environmental impact. The costs are primarily associated with investment, construction, and operation, whereas the risks and benefits correspond to the sustainability indicators. In general, employing these technologies for FEW sectors provides benefits associated with reduction in carbon, water, and ecosystem footprints.

3.3.2. FEW systems in Amsterdam Metropolitan Area, The Netherlands

3.3.2.1. Study region. The Amsterdam Metropolitan Area (AMA) is located in the North-Wing of the Randstad, the major urban area in the Netherlands. The AMA is not a governmental entity, but a corporation with 32 municipalities including, and around, the municipality of Amsterdam. These municipalities together cover at least 2580 km^2 of land (CBS, 2018), which is almost 6% of the total area of the Netherlands. One of the greatest challenges of the AMA is population growth. In 2018, the city of Amsterdam and the AMA included around 0.8 million and 2.4 million citizens, respectively (CBS, 2018). The prognosis is that in 2025 the population of the city of Amsterdam will grow to 0.923 million inhabitants, and reach 1 million before 2040 (OIS Amsterdam, 2018). In the city of Amsterdam, it is therefore expected that 89,900 extra houses will be built between 2018 and 2040 (OIS Amsterdam, 2018). In the AMA, it is expected that there will be an increase of 230,000 households in the same time period (Metropoolregio Amsterdam, 2017).

Another challenge is climate change adaptation and mitigation (Van der Hoek et al., 2017; De Stercke et al., 2018). A change in climate has already been measured. Between 1950 and 2010, the Royal Netherlands Meteorological Institute (KNMI, 2018) measured an increase of 1.6 °C of the yearly average temperature in the Netherlands. Additionally, an increase in yearly rainfall was measured from 769 millimeters in 1901 to 933 millimeters in 2010. The rainfall will not only increase but will also intensify. The report also shows that during winter and summer there will be more extreme rain events. In summer, the number of rainy days will decrease, which might lead to a further increase of precipitation deficits in summer. Urban heat islands could be exacerbated in the AMA. Other challenges connected to climate change in the Netherlands are sea level rise and saline water intrusion. National policy aims to tackle these challenges in several ways, including transitioning toward a circular economy and zero carbon emissions by 2050 (Circular Economy, 2016; Ministry of Economic Affairs, 2017). This involves some national policies that, for example, promote the transition of home heating systems from gas-fired space heaters to electric space heaters to reduce *greenhouse gas (GHG) emissions*. Therefore, a FEW nexus approach can provide insight into the interdependencies between the three resource systems that contribute to sustainable methods for the mitigation of climate change impact.

3.3.2.2. Integration of technology for urban greening. This nexus system has adopted a strategy with the potential to reduce carbon emissions via the sequestration of carbon by urban green areas. Strohbach et al. (2012) took a life cycle approach to the carbon footprint of urban green spaces in the city of Leipzig, Germany. In their analysis, they included the carbon emissions produced by the maintenance and transport of fertilizers, which proves to be relevant in the carbon footprint analysis. We argue that such an approach would be relevant for developing a good understanding of the potential for climate change mitigation by urban green spaces. Such areas can include trees, shrubs, and herbs, and can be located on the ground, on walls, on roofs, and within buildings, in addition to the MUP with salient industrial symbiosis, all of which is described in Figures 3–8 of Part I of this series.

3.3.2.3. Site of application. The integration of green areas in the city is distributed within the urban boundaries and is performed by different actors. The map below indicates different green roof initiatives in the city of Amsterdam (Figure 9).

3.3.2.4. Potential impacts for FEW systems. Green spaces are often lauded for their ability to cool cities and reduce the effect of urban heat islands (e.g. City of Amsterdam, 2015). However, academic research on the quantification of ecosystem services from urban green spaces seems, to our knowledge, to be based on a case by case basis. Quantification of ecosystem services at a higher spatial and thematic resolution has proven to be difficult (Derkzen et a. 2017). It is possible to explore the potential of urban green spaces by focusing on the application of green roofs. The focus points are (a) carbon storage, (b) energy use reduction by insulation, (c)

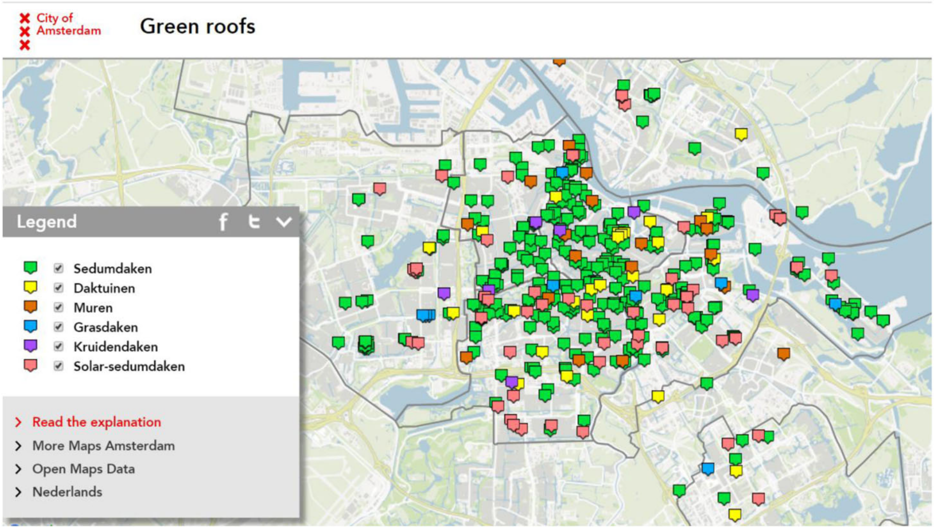

Figure 9. Indication of green roofs in the City of Amsterdam, the Netherlands (https://maps.amsterdam.nl/groene_daken/?LANG=en, accesses 30 January 2019).

energy use reduction by cooling, (d) sustainable urban farming, and e) potential energy resources such as biofuel production. These points are described separately in detail below: 1) Carbon sequestration: Research has shown that, for the case of Leipzig, carbon mitigation by green spaces was not significant compared to the emissions from people (Strohbach et al., 2012). Trees are more effective in offsetting carbon emissions than other types of green areas, such as green roofs (Derkzen et al., 2017). 2) Energy reduction by insulation: Santamouris et al. (2007) found that green roofs did not significantly reduce the heating load of a school in Greece. 3) Energy reduction by cooling: Santamouris et al. (2007) found a significant contribution to energy efficiency within a building (6-49% depending on the location within the building) by a green roof. Other research pointed out that green roofs made of sedum plants do not necessarily reduce the temperature outside the building (Solcerova et al., 2017). Nevertheless, the same research showed that green roofs can have a cooling effect during the night, when the effect of urban heat islands is the strongest. 4) Sustainable urban farming: Urban farming is gaining popularity in the Amsterdam Metropolitan Area (Van der Schans, 2010). Not only can food be grown in urban green spaces, but also biomass may be harvested for the production of energy. The MUP of Amsterdam, described in section 4.2.2, has the potential to contribute to the FEW system. 5) Sustainable heating in winters: Gas vs. electricity heating was evaluated due to the movement of national policy that largely affects greenhouse gas emissions in the future.

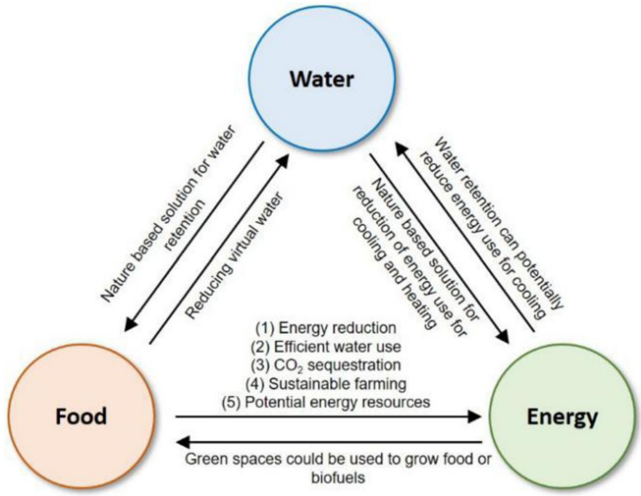

Figure 10. Conceptual diagram demonstrating the interdependencies and interconnections in the FEW nexus for urban greening in Amsterdam, the Netherlands.

In Figure 10, green space could be used to grow food for biofuel ("energy for food"), while water retention can potentially reduce energy for cooling ("energy for water"). There are five options, including (a) carbon storage, (b) energy use reduction by insulation, (c) energy use reduction by cooling, (d) sustainable urban farming, and e) potential energy resources such as biofuel production ("food for energy"). Increasing rainfall due to climate change coupled with a nature-based solution via open green space can also be used to reduce energy use for cooling and heating ("water for energy"). Water retention from a nature-based solution can be used for improving food production ("water for food") and, in turn, reducing food imports as a result of local food production to offset external food demands and aid in virtual water delivery ("food for water").

In this city-wide FEW system in Amsterdam, the potential costs, benefits, and risks of associated technologies (highlighted in Sections 3.1-3.2 of Part I) have to be flexibly evaluated toward limited planning scenarios, culture-orientated thinking, and site-specific characteristics in the future. Yet sustainability assessment of such a nexus with an emphasis on green space contribution should be evaluated in terms of water, carbon, and ecosystem footprints together given the local climate variability. The ecosystem footprints may be modeled by means of a suite of separate modeling efforts. Moreover, the analysis of the possible cost-benefit-risk tradeoff for the adoption of green roofs in conjunction with MUP in this metropolitan region are important for decision-making and optimization. The comparison of the cost, benefits, and risk associated with the three sustainable indicators for each technology can ultimately aid in determining which FEW system alternative is most feasible.

As mentioned, the application of green roofs and green spaces minimizes carbon footprint, reduces heat island effect and reduces cooling, thus indirectly reducing energy demand and GHG emissions. Additionally, it provides urban farming for local food consumption or cultivation of crops for biofuel production. The installation cost is minimal, although crop growth competition and long maintenance times are risks to consider. The irrigation for the maintenance of green roofs can be supplied from stormwater collected, reused, and harvested during the wet periods, or from reclaimed wastewater. Stormwater harvesting reduces the water footprint by decreasing the demand for water resources.

The MUP of Amsterdam contains a waste to energy (WTE) facility, a wastewater treatment plant (WWTP), and a landfill for the incinerated ash and WWTP biomass. The MUP can offer high temperature steam and electricity for direct household heating. This additional supply chain reduces the demand for and reliance on utility grid electricity while reducing carbon and ecosystem footprint via the decrease of waste disposal. Without MUP, the operation capacity of WTE plants depends solely on the efficiency of waste collection and recycling; this risk can be minimized, provided the landfill waste disposal and biomass flows are constant. Landfill methane gas recovery for WTE can become additional benefits. To maintain low environmental impacts, pollution control systems and fly ash reutilization in manufacturing are necessary. Lastly, cost will be associated with the operation and maintenance cost of the WTE and WWTP facilities. According to Figure 10, the MUP can enhance the interdependencies and interconnections by providing high temperature steams from WTE and methane gas from WWTP for district heating to replace the natural gas in winters ("water for energy"), as well as biomass and reclaimed wastewater for food production ("water for food"). Electricity produced by the WTE facility can support food production ("energy for food") and water recovery and delivery ("energy for water"), as well.

3.3.3. FEW systems in Marseille, France

3.3.3.1. Study region. Marseille is the second biggest city in France in terms of population. It is located at the south coast, covering an area of 241 km^2. The city has more than 850,000 inhabitants and its larger metropolitan area (3,173 km^2) has a population of 1,830,000. The city was built directly on the coast of the Mediterranean in the Bay of Marseille, running along 57 kilometers of coastline (Figure 11). The city spreads itself from the coast to the surroundings hills; thus, several districts are placed on the slopes or on top of these hills. The city of Marseille is an important hub for trade and industry in the south of France, which is linked to its extensive infrastructure. The new commercial port of the city is the biggest in France and the

Figure 11. Location and area of intervention of Marseille, France.

fifth largest in Europe by cargo tonnage, representing a leading factor in the Marseille economy. Petroleum refinery and shipbuilding are the biggest industrial sectors. Marseille is the country's leading center of oil refinement, and petroleum is transported to the Paris region via pipeline. Other important industry sectors are the production of chemicals, soap, glass, sugar, building materials, plastics, textiles, olive oil, and processed foods. In recent years the service sector, as well as the high-tech economy, has gained increasing importance.

3.3.3.2. Main upcoming challenges for Marseille. The upcoming challenges for sustainable development in Marseille include the impacts of climate change and global warming (growing heatwave frequency and intensity, heavy rainfall events related to Med sea temperature increase at the end of summer), potable water supply, wastewater treatment and discharge, energy supply (especially renewable energy sources via a marine geothermal plant), and the production of foods and vegetables locally, along with the maintenance of vegetated public gardens. To overcome these challenges, the FEW approach may be implemented in the Euroméditerranée area in Marseille. The first part was built in the last ten years (Euromed1), and a second (Euromed2) will be built at a formerly relinquished district. The first building already exists, and the rest will be built over the next 5 to 10 years.

3.3.3.3. Planned FEW systems in Euromediterranée, Marseille. The main challenges and the main initiative in terms of the FEW nexus for Euroméditerranée are shown in Figure 12. Within the proposed FEW system, the links with energy, for example, include: 1) expansion of the

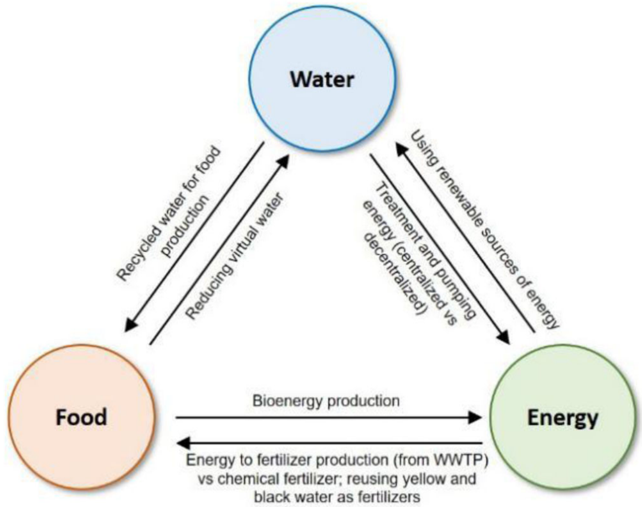

Figure 12. Conceptual diagram demonstrating the interdependencies and interconnections in the FEW nexus for urban greening in Marseille, France.

current marine geothermal plant to support the cooling operation in the building complex and the rooftop food production in the port region, 2) energy to treat nitrogen (N) and phosphorus (P) in Marseille WWTP (centralized) and to produce chemical fertilizers vs. to reuse yellow and black water as fertilizers, and 3) energy consumption for air-conditioning systems (vegetated areas that decrease urban temperature vs. no vegetated areas in urban farming zone) ("energy for food"), as well as using renewable energy for irrigation and cooling ("energy for water"). Performing rooftop urban farming may, in turn, reduce food imports as a result of local food production to offset external food demands, which can help reduce virtual water consumption ("food for water"), and urban farming may help produce biofuel as well ("food for energy"). Energy recovery from the Marseille WWTP can be used to reduce the reliance on utility grid energy for cooling ("water for energy") and support food production ("water for food"). Part of the aforementioned aspects will be implemented in the FEW nexus in Marseille gradually throughout the upcoming years. More focus has been given to water loops and renewable energy production (marine geothermal plant) in regard to urban farming and urban cooling due to constant heat wave impact in summertime, and nutrient reuse in the FEW system under climate change impact.

In this FEW system nearby the port area in Marseille, the potential costs, benefits, and risks of associated technologies (highlighted in Sections 3.1-3.2 of Part I) have to be evaluated in the future with respect to planning scenarios regarding heat wave and thermal engineering with culture-oriented thinking and site-specific characteristics. A sustainability assessment of such a nexus with an emphasis on carbon footprints should be evaluated given the local climate variability. The ecosystem footprints may not be salient given the local conditions. Depending on the sociocultural context, the availability of resources, and demand, the adoption of FEW technologies would vary.

3.3.4. Synthesis for the three coastal FEW systems

With an emphasis on the reduction of carbon, water, and water footprints, the following FEW technology alternatives are proposed for the urban regions of Miami (DBP), Amsterdam, and Marseille (Euromediterranée) in France. When looking into the three case studies, synthesis can be carried out in terms of cost-benefit-risk factors. To determine the optimal integration of the FEW technologies, the analysis of the cost, benefit, and risks in terms of the three sustainability indicators for each metropolitan region is summarized by Table 2. It is noted that the costs are primarily associated with investment and O&M of the technology, and thus minimizing these costs is preferred, although the costs associated with the gain and loss of the corresponding sustainability indicators are better described as risks. The distinction between risks and benefits for technology adoption between water, carbon, and ecosystem footprints is more complicated given that a specific technology may contribute to carbon footprint reduction while concurrently affecting the water footprint. Based on the difficulty in decision-making due to the many variables for consideration, the tradeoffs can be assessed through decision-making strategies and governance structure.

For implementing the integrated FEW nexus and enhancing environmental sustainability, green energy (photovoltaic systems) (S1-PVS), anaerobic digestion for biogas production (B1-BF/ B3-BP); LID (retention/ detention pond (SW1-RB) and rainwater harvesting/storage facilities (SW9-GR)); and dripping irrigation (UA12-SDI) and hydroponics (UA1-H) systems have been proposed in the DBP. The goal of this FEW nexus is to promote food security from urban farming, and energy self-reliance while minimizing carbon, water, and ecosystem footprints at a community scale. The use of retention water (SW1-RB) for food production, sustainable farming (depending on suitable technologies listed in Part I), energy reduction through sustainable design (e.g., insulation), biofuel and bioenergy (B1-BF, B2-WP and B3-BP), use of green space (for reducing the urban heat island and cooling demand), etc. are the highlighted potential FEW technologies in Amsterdam. Since the primary challenge and concern for the Amsterdam Metropolitan Area in the Netherlands is its population growth, planning for the increase in development while mitigating the carbon, ecosystem footprint, and environmental impact is crucial. The proposed technology integration for the FEW nexus system focuses on reduction of carbon footprint through carbon sequestration by urban green areas such as green roofs. The inclusion of MUP contributes and enhances the FEW system. In Marseille, the potential FEW nexus would include the use of recycled water (WWT2-CT/ WWT3-DT) for food production, using renewable sources of energy (depending on suitable technologies listed in Part I), bioenergy production (B1-BF, B2-WP and B3-BP), WWTP to fertilizer production, etc. Since one of the current renewable energy sources is marine geothermal energy, focusing the FEW system in Marseille on bioenergy can further reduce the use of petroleum-based products in the local industry. Further, the inclusion of urban farming, water recycling, and nutrient reuse minimizes carbon and water footprints. Less impact is also experienced for the ecological footprint, as mining for nutrient acquisition for fertilizers is reduced.

3.4. Challenges for innovations of urban FEW systems

Studies in Section 3.3 provide a vital viewpoint that allows readers to see the real-world complexity. We argue that a case specific FEW nexus should be used in an urban system analysis with respect to different socioeconomic and cultural contexts for enhancing urban sustainability and supporting decision making processes by integrating technologies for tradeoffs in terms of cost, benefit, and risk with respect to sustainability criteria. However, technology hub integration in different scenario analyses may encounter multifaceted challenges, which will be discussed in the following subsections.

3.4.1. Nexus themes, issues, sustainability criteria, and indicators

FEW nexus covers a wide range of themes and issues with a variety of scales that have been analyzed via a myriad of approaches, tools, frameworks, and techniques. The common themes of FEW nexus mainly include resource scarcity (Dubreuil et al., 2013), the realm of sustainability (Hussey & Pittock, 2012), and climate change impacts (Howells et al., 2013). Furthermore, the specific issues of FEW nexus that have received particular attention include, but are not limited to, water (Uddameri & Reible, 2018), groundwater (Gurdak et al., 2017), wastewater (Kurian, 2017), food (Zimmerman et al., 2018), agriculture and land (Tian et al., 2018; Chen et al., 2018), fisheries (Endo et al., 2017), food waste (Kibler et al., 2018), energy (Ali, 2018), the integration of climate change adaptation plans and climate vulnerabilities (Rasul & Sharma, 2016; Howarth & Monasterolo, 2017), environmental impact (particularly GHG emissions) (Zhang & Vesselinov, 2016; Bieber et al., 2018), managerial policies (Kaddoura &

Khatib, 2017), and the integration of two or more of these issues for hybrid analyses (Garcia & You, 2016; Hussien et al., 2018; Bullock & Bowman, 2018).

In relation to climate adaptation, 28 nexus studies were identified from the prevailing nexus research with varying levels of integration of different FEW systems (Rasul & Sharma, 2016). In a recent study, Li et al. (2019) identified 87 representative factors (issues) for various FEW systems based on the structural modeling method. Nevertheless, the method of carrying out the synergistic consideration identified in previous case studies is still a big challenge in urban FEW systems, as urban FEW systems are oftentimes associated with different complex themes and issues. Although studies of FEW nexuses have been growing rapidly in the past few years, nexus research methods have yet to mature. Specifically, the integration of technology hubs into urban FEW nexuses is still evolving, as new technologies emerge quickly and are available for sustainable and resilient urban developments.

One of the fundamental challenges is the selection of sustainability indicators lying at the core of the interdependencies and interconnections of FEW sectors, both of which are dependent mainly on individual preference based on predetermined nexus criteria, their study objectives, and the scale of study. In the prevailing nexus studies, only limited indicators were used at the discretion of researchers. These indicators include, but are not limited to, water footprint, energy consumption, carbon footprint or GHG emission, ecosystem footprint, etc., for environmental sustainability, in addition to policy, governance, social networks, etc., for social sustainability and capital investment, and operation and maintenance costs, etc., for economic sustainability. The method of determining a set of suitable indicators is still unclear.

Several studies have considered multiple indicators in different types of nexus analysis. For instance, Saladini et al. (2018) used 12 indicators for FEW nexus analyses in the Mediterranean area, including poverty index, potential land use, GHG emissions, cereal yield, freshwater consumption for agriculture, agricultural residues for energy, etc. Yuan et al. (2018) used the mid-point and end-point indicators based on the IMPACT 2002+ life cycle impact assessment (LCIA) method to analyze the bioenergy production from rice straw in a food-energy nexus in Taiwan. A tele-connected FEW nexus approach was developed and applied based on the MRIO modeling in East-Asia with several indicators such as water, energy, land requirement, and air pollution (i.e., CO_2 and SO_x emissions) (White et al., 2018). Wang et al. (2018) studied waste-to-energy pathways in relation to different waste and wastewater treatment technologies based on LCSA. In this study, the environmental impact categories were organized based on the CML LCIA method (i.e., the mid-point approach developed by the Institute of Environmental Sciences, Leiden University, the Netherlands), and cost-subcategories, including operational cost, capital cost, and labor costs were adopted for LCC analyses. However, some of the upstream impacts, land use, ecosystem services and damages, potential health impacts, cost-benefits, etc., of different systems or technologies are essential to integrate for evaluation in the FEW nexus. In addition, the existing nexus frameworks are unable to adequately incorporate sustainable livelihoods perspectives (Biggs et al., 2015). Discussions of prioritization, incorporation, and cross-linking of themes and issues are still missing between the three resource sectors (Al-Saidi & Elagib, 2017). Integrated assessment of a FEW nexus with optimization schemes is thus important for a multicriteria decision-making process. While a FEW nexus requires an essential measure for achieving sustainable development goals, transformation of multilevel governance at different levels would smooth out the implementation of a FEW nexus and, in turn, affect the multicriteria decision-making process (Pahl-Wostl, 2019).

The development of indicators and benchmarking is essential for measuring the sustainability performance of cities with respect to potential future scenarios (Boyko et al., 2012). However, no specific nexus indicators are evident so far, as previous studies were mostly based on researchers' individual preferences regarding the selection of indicators. The consideration of indicators in the nexus study that represent local, regional, and global significance is therefore a challenge. This may be due to the lack of extensive data and comprehensive analytical framework, as the selection of a wide range of indicators would need plenty of data (both upstream and downstream) along with multiple modeling tasks for model calibration and validation. To enlarge the holistic insight, the relevant indicators selected by some case studies are summarized in Table 3.

The assessment of technology hub integration in practice is a prerequisite for any nexus sustainability performance. For ensuring the criticality of urban FEW innovations, it is thus necessary to screen and select a suite of critical sustainability indicators, such as carbon, water, and ecosystem footprints, for all scenarios when these FEW technology hubs are used discretely for integration in a decentralized FEW system, for a FEW system wherein the technologies are integrated with industrial symbiosis relationships in a centralized system, or for any hybrid systems between a centralized system and a decentralized system.

3.4.2. Scaling effect of different FEW systems

The scales of current nexus studies vary widely from micro-level (Kucukvar et al., 2016; Uddameri & Reible, 2018; Hussien et al., 2018), to macro-level

Table 3. Examples of some nexus research with practical case studies.

Study	Aim	Nexus scale	Nexus highlight	Methodology	Used tool(s)	Principal data	Sources of data	Selected indicator(s)	Implications (key findings)	Challenges
Yuan et al. (2018)	Environmental impact minimization model under FEW nexus	National (Taiwan)	Bio-energy (E-F)	LCA; linear programing; GIS	SimaPro, ArcGIS	Bioenergy production, crop cultivation.	Databases, literature, reports.	Mid-point and end-point indicators based on Impact 2002+ LCIA method.	Energy generation from bio-coal produced from rice straw is environmentally beneficial; food and energy self-sufficiency can be enhanced by bioenergy from such biomass.	Limits to bioenergy production only without considering the water demand; effects of political changes (e.g., on energy production) were not highlighted; economic feasibility was not considered; integration among the three systems were not focused.
Zhang, Campana et al. (2018)	Agricultural drought management system by using FEW nexus modeling and optimization approach	Local (Nebraska, USA)	Food	GIS; Generic algorithm	GIS-OptiCE	Geospatial, agricultural datasets, meteorological data, remote sensing data, agricultural production statistics.	Databases, literature, reports, statistics.	Economic indicators such as water price, irrigation system, corn price; crop (corn) yield, energy requirement, water consumption for crop production.	Implementing irrigations system is economically feasible for combating drought effects, but significant investment is required.	Demand for higher energy requirement for pumping; long-term forecasting and feasibility is needed; hydrological model that evaluates the water balance at spatial and temporal scales is needed in integration and optimization.
White et al. (2018)	IO approach based on transnational interregional is utilized in a tele-connected FEW nexus analysis in the East Asia	Regional (East-Aisa)	Water, food, energy	Environmental input-output analysis; Generic algorithm	MRIO	Regional economic flows, bilateral trade data, environmental emission, resource consumption	Reports, statistics, modeling, databases.	Water, energy, agriculture land use, scarce water, and GHG and SOx emissions.	The water, energy-food consumption drivers are not only associated with specific geographical and ecosystem boundaries; lack of environmental impacts consideration into trade policies.	Data accuracy is the main constraint of such study; lack of sector-specific data also hinder its application; MRIO model can provide a general feature of a region rather than a sector specific nexus analysis.
Wang et al. (2019)	Evaluated energy–water nexus scenario analysis framework in China based on future energy scenarios.	National (China)	Water, Energy	Extending input–output analysis	Input-Output modeling	Energy consumption data for 30 sectors	China Statistical Yearbook.	Total energy generation, nonrenewable energy, coal, water pressure, energy-related water, and carbon emission.	Higher nexus impact on the water system was demonstrated than that on the energy system; consuming the least coal with the highest non–renewable energy usage can impose the lowest energy-related water consumption.	Tradeoffs among the studied 5 scenarios needed to be deeply investigated in order to obtain the least energy and water consumption, carbon emission, and higher renewable energy consumption; interdependency among the nexus systems needed to be further investigated.
Moioli et al. (2018)	Sustainability of bioenergy production under nexus perspective	Global (191 countries)	Bio-fuel	–	Mathematical equations for calculating the nexus index	Crop yield, land use, bio-fuel production, water consumption	FAOSTAT, World Bank, literature, statistics, modeling.	Nexus index (the use of FEW resources is necessary to get	Presented country specific efficiency of managing biofuel production from a specific crop; water	Nexus index is proposed based on a board aspect, it may often mislead as the data is mainly based on broad

								the final output energy).	management is the most crucial parameter to sustainable design; may contribute to bio-fuel policy for a country.	statistics; in addition, a particular crop may not be used for energy purposes only.
Xue et al. (2018)	Proposed an online open access tool for cities to analyze circular economy scenarios associated to FEW management	Local (Beijing, China)	Policy nexus	Emergy-based urban dynamic(system) model	Urban Circular Economy Calculator; Vensim® PLE software	Energy-water policy nexus, water-energy policy nexus, etc.	Government documents.	–	Over 20 circular economy policies related to food, energy and water were under 6 categories, including the energy for the water operation system, energy for water use, role of bio-fuel, food waste and energy, biodiesel, food production and consumption, water quality and quantity; as a circular economy supported tool, it can be used to promote sustainable transition of a city and can be integrated in a urban resource management system	Results were provided based on the existing policies. However, changing policies due to technological improvements (and changing pattern of resource usage) may significantly influence the outcomes; in addition, sector-specific policy analysis in the nexus system may need to integrate for better accuracy of the results; data acquisition and practical case study to support such policy results are important to validate
Salmoral and Yan (2018)	Evaluated the virtual water (upstream) and energy (embodied) in food consumption	Local (Tamar catchment, South West England)	Food	LCA, mathematical modeling	SimaPro, Generic algorithms	Purchased food products	DEFRA, LCI datasets (agri-footprint database).	Embodied energy, blue water and green water.	The study illustrated upstream water and energy requirements in the food life cycle by highlighting the potential FEW risks and tradeoffs for the food supply-chain; in the studied region, imported food products are responsible for 51% of the total embodied energy, 88% blue water, and 42% green water.	Limited types of food products were considered; specific LCI database are spatially (and also temporally) representative; food products imported from other UK regions were not considered, rather overseas only; limited to a few indicators in the assessment.
Al-Ansari et al. (2017)	Greenhouse gas control and waste to energy technologies integrated FEW nexus to evaluate the environmental impact of food product system	National (Qatar)	Food	LCA	Generic algorithms	Fertilizers production, livestock production, agricultural activities, power generation, water consumption	LCI databases, literature.	GHGs emission, human toxicity, acidification, land use.	The study found that GHG emissiosn can be theoretically balanced by integrating photovoltaics, biomass integrated gasification technologies and carbon capture technologies in the studied sectors.	Sensitivity of the technology adoption, technological uncertainty and feasibility, economic feasibility, etc. was not considered; policy issues about the technology adoption and impact mitigation were not highlighted; comprehensive LCI is lacking which is very important for such a LCA nexus study.
Wang et al. (2018)	Analyzed waste-to-energy pathways for sustainable urban energy-water-waste nexus development	National (Ghana, sub-Saharan Africa)	Energy	LCSA; Optimization	Mixed-integer linear programing	Waste treatment, energy generation, power technologies	LCI databases, literature.	Indicator (GHGs) based on CML baseline LCIA; Economic (investment,	Waste-to-energy adoption leads the energy sector toward a low-carbon transition; however, the adoption of advanced carbon capture	Only electricity was considered, while other energies such as heat and fuel were not considered; very limited LCSA indicators were

(*continued*)

Table 3. Continued.

Study	Aim	Nexus scale	Nexus highlight	Methodology	Used tool(s)	Principal data	Sources of data	Selected indicator(s)	Implications (key findings)	Challenges
								operation and maintenance costs).	and storage technologies are important for long-term sustainability.	adopted, this may be due to the lack of comprehensive data; sensitivity of the waste-to-energy technology adoption, technological uncertainty and feasibility, etc. was not considered; policy issues about the technology adoption and impact mitigation were not highlighted.
Hanes et al. (2018)	Considering resources constraints, optimization of food and energy co-production system was evaluated based on energy-food nexus.	Local (Ohio, USA)	Food and energy	Optimization	Mixed-integer linear program	Land use, food production, energy generation, energy technologies and conversion (solar PV, biomass, wind turbines), reforestation, wetland	Databases, literature, reports, statistics.	Energy, air quality, water quality, climate regulation, food production.	Integrated system of wind and solar with food production is the most productive and sustainable co-production systems in the local conditions.	Considered single-objective optimization (co-production only); in nexus analysis, multiobjectives optimization by including the land use options, farming practices, prices of food and energy, quality of local land, and other factors are needed to be critically considered.
Chen et al. (2018)	Based on the demands for water and energy resources, the impacts of growth under different water and energy production and consumption scenarios of city was evaluated	Local (Hong Kong)	Water and energy	Mixed–unit input–output analysis	Generic algorithms	Water supply, energy supply	Literature, reports, statistics.	Water demand, energy demand.	Water for energy and energy for water will increase by 7.8–9% in 2050 in Hong Kong.	Narrowly analyzed the water and energy supply without considering the technological and policy changes in both water and energy production and supply.
Uddameri and Reible (2018)	Analyzed the feasibility of brackish groundwater development for improving water resiliency in a drought prone semiarid region under FEW nexus	Local (Texas, USA)	Water	GIS	ArcGIS, Generic algorithms	Water level data for aquifers, water quality data, water supply, energy requirements	Government data sources, literature.	Water quality and requirement, energy requirement.	Desalination is not a feasible option for agricultural irrigation, as 4-5 times higher energy required for desalination, but may be an option for municipal water supplies to decrease the pressure on the studied aquifer (shallower Ogallala Aquifer) and also improve its longevity.	Much focused-on water resources using GIS which is very important for such local conditions; however, a more integrated FEW study is needed that focus on different cropping systems (may be water resilient) and energy options.

(Garcia & You, 2016; Sušnik, 2018; Chen et al., 2018) and in size from urban district to regional scale (Chen et al., 2018b; Zhao et al., 2018), to river basin scale, to national (Voltz & Grischek, 2018; Sperling & Ramaswami, 2018), to global (Kurian, 2017; Chen et al., 2018), all of which require different approaches and strategies. The micro-level study primarily focuses on evaluating resource flows in specific sectors at the community scale, e.g., evaluating and/or forecasting carbon or water footprints for a specific sector, such as energy or food production, and vice-versa. Yet resource availability, management, and forecast are considered for multiple sectors in different geographical scales (e.g., city, region, state, country, or transboundary regions) in macro-level nexus studies (Retamal et al., 2009; Bazilian et al., 2011). Spatial scales should receive higher attention, particularly in the, albeit complicated, policy-related nexus analysis (Bijl et al., 2018).

Each scale of a nexus study has its unique characteristics and importance. Case-specific local FEW studies are important for achieving local sustainable development goals, as well as for targeting high level objectives. However, a nexus on a national scale is important for analyzing the current state of resource use holistically, as well as for future projection nationally. Lee et al. (2017) conducted a case study at a regional-level nexus to ensure an improved understanding of the use of water and energy regionally, and to achieve maximum benefits from the nexus system. Abdelkader et al. (2018) analyzed the food and water scenarios in Egypt based on the national food-water model. The study projected that water and food gaps will be inevitably widened in Egypt in the future, mainly due to population growth and its consequent demands for more resources. However, the physical challenges for managing resources over a large geographic region associated with different sovereignty over regional policies are the main barriers in a regional FEW system (Schreiner & Baleta, 2015). In addition, global availability, flow of resources, and the use of resources can be highlighted based on a global scale FEW nexus. For example, Taniguchi et al. (2017) emphasized that highly diversified sources of water are available in the United States and the Philippines, yet this is not the case for food in the United States, Canada, and Indonesia. This observation was mainly drawn from two water sources, the surface water and the groundwater, for calculating water diversity; four sources of energy including coal, oil, gas and renewable energy for energy diversity; and five sources of food including cereals, vegetables, fruits, livestock, and fish for food diversity.

Overall, how the effects of technology hubs cascade across spatial scales in a FEW nexus, how the local and regional FEW systems are linked via technology hubs, and how the cross-scale interactions can be explored, are intricate and intertwined in applied system analysis. The implication of nexus research with different scales and nexus highlights is summarized in Table 3.

3.4.3. Challenges of integration among simulation, forecasting, and optimization models

Numerous methodological challenges are associated with the evaluation methods of an urban FEW nexus in terms of methods, tools, data collection, indicators, physical boundaries, resource consideration, stakeholder involvement, etc., as no standard method has been developed yet. Although nexus studies have focused on specific aspects of nexus systems, several improvements in the methodology, especially method adoptions, were observed. Some of the case studies with different methods can be found in Tables 1 and 2. As the nature of the nexus approach is often dynamic, the definition of physical boundaries is a challenging, but important, task for real-world nexus implementations.

Although some of methods are valuable for nexus research in specific sectors, many of them are unable to capture interactions across nexus components due to a deficiency of data sharing and data availability (Shannak et al., 2018). As the studies are often dependent on data from government reports and literature, this dependence may induce greater uncertainty due to the quality and availability of data, aggregated data, and inconsistent reporting (Ernst & Preston, 2017). Thus, the extensive data requirements and poor affinities between tools for assessing individual nexus areas are the main limitations of existing nexus tools. The appropriate selection of multiple methods is required to evaluate integrated urban FEW nexuses effectively, although it is time consuming, complex, and constrained by available data.

There are manifold technological challenges associated with urban FEW nexus implementations. Due to their dynamic nature, the integration of different technologies in differing FEW systems is one of the main challenges. These challenges include, for example, the adoption (or changes) of renewable energy technologies and gray water recovery for food production, waste materials for energy generation, and renewable/alternative energy for water purification with respect to existing policies in various urban FEW systems. One specific tool or method cannot effectively evaluate such a complex and large-scale system with interconnection and interdependence. In addition, only a very limited number of analytical tools are available that can address all FEW systems, and these require transdisciplinary thinking for analyzing the nexus (Shannak et al., 2018). Thus, multiple tools for dealing with different aspects of FEW nexuses should be employed for possible improvement across the sectors, and comprehensive consideration of data quality and data sharing are necessary for robust modeling when dealing with interlinked resource systems with the aid of advanced sensing, networking, and control technologies (Abegaz et al., 2018).

Developing a FEW model that can incorporate multiple scales, dimensions, uncertainties, sectors, agents, and impacts is essential for addressing multiple externalities and policies for sustainable FEW systems (Kling et al., 2017). So far, for instance, most of the cities' climate actions or sustainability plans highlighted climate impacts without addressing other impacts (particularly those due to sea level rise, changing rainfall patterns, etc.) simultaneously. The majority of them primarily focused on only GHG mitigation and ignored challenges of resource depletion and FEW linkages (Sperling & Ramaswami, 2018). The most inextricable issue is related to challenges in dealing with multiscale and multiagent modeling structures when modeling various urban FEW nexus systems. Nexus systems are intimately linked to the definition of an appropriate system boundary, integration of temporal and spatial scales, life cycle assessment over the temporal domain with an optimization scheme, and modeling of the role of multiple stakeholders. As a governance organization influences food, water, and energy management, it is still unclear how relevant policy frameworks can guide the decision-making process across multiple decision makers and stakeholders toward governance or policy coherence (Weitz et al., 2017). Howarth and Monasterolo (2016) argued for the integration of different aspects, including communication and collaboration with relevant parties, decision making processes impacting policies, and social and cultural dimensions regarding the nature of responses to nexus shocks. Therefore, integrative challenges include the integration of resource use; supply and demand of resources; environmental, social, and economic sustainability; and policy influence, as well as decision making processes.

The efficiency of FEW resource use should be approached by not only managing multidimensional tradeoffs, but also by mitigating risk and enhancing synergies (Cai et al., 2018). Thus, optimization (i.e., spatially, temporally, sectorally) between resource use, environmental and social impacts, benefit-cost analysis, etc., within a FEW nexus is necessary. Some of the optimization techniques suitable for FEW nexus studies have been adopted by a few studies and these efforts mostly focused on optimizing the planning, design, or operation alternatives based on a few sustainability indicators or resource constraints (Wang et al., 2018). Yet optimization by including the multiple resources and indicators in urban FEW systems has not been effectively developed and implemented. Data collection for the evaluation of FEW systems is the main hindrance for conducting such optimization. For example, Hanes et al. (2018) analyzed a local FEW issue based on a single-objective optimization model in the United States. The study evaluated the energy and food nexus by optimizing the food and energy co-production system under resource constraints (e.g. ecological sustainability, constraints on food and energy production, etc.). Multi-objective optimization was used by Zhang, Campana et al. (2018) to study agricultural drought management under a FEW nexus. Their study discovered that irrigation can help relieve the negative effect of drought on corn production, but significantly higher investment in water and energy is required. The study also concluded that the optimal crop yield is not essentially related to the maximum crop yield due to the inherent complexity of the nexus. Thus, future assessment of different urban FEW nexuses should focus on how to promote the efficacy of resource tradeoffs and maximize synergies among resources while optimizing multiple variables of concerns and co-optimization of various subsystems, and how such optimization schemes could vary across different scenarios with the inclusion of more sectors, given future environmental changes.

3.5. Perspectives for urban FEW systems analysis

This review paper provides a comprehensive overview of the current status of FEW nexus research by analyzing the contemporary issues arising from the integration of technology hubs and the associated cost-benefit-risk concerns via three recent case studies in Miami, Amsterdam, and Marseille. The philosophy of applied system analysis for managing various FEW nexuses can be developed by investigating possible tradeoffs among costs-benefits-risks of existing and emerging FEW technologies within different technology hubs. Integration of technology hubs with case-based engineering practices at different scales in the USA and Europe were highlighted. By analyzing some of the featured literature, relevant themes and issues were critically examined with respect to challenges and limitations in practical implementations. Based on these extensive discussions, key research questions, including the potential solutions for urban FEW nexus research, are summarized, and the development of a theoretical urban FEW framework with the integration of technology hubs, indicator settings, and FEW nexus evaluation is finally proposed for holistic urban sustainability assessment. However, Wichelns (2017) pointed out that the current efforts to implement a FEW nexus may not be able to enhance policy settings. This may be due to the lack of a commonality in methodologies and support in conceptual frameworks across the current FEW nexuses. Since there are no standardized methods, tools, or approaches for analyzing various FEW nexuses with different spatiotemporal scales, many studies are still at the "understanding" stage of various FEW nexus analyses (Dai et al., 2018).

Moreover, Zhang and Vesselinov (2017) suggested the community should include resource constraints and environmental protection in practical

FEW nexus applications. Although intersectoral tradeoffs across the three sectors (e.g., food, energy, and water) with some external factors (e.g., population growth) and natural vulnerabilities (e.g., climate change) are included in many nexus studies, integration of risk assessment in a FEW nexus is scarce (Dargin et al., 2019). However, a micro-level FEW nexus model was developed for a sustainable water supply by highlighting seasonal variations, as documented by Hussien et al. (2018). The study evaluated the impact of water, food, and energy consumption based on the seasonality effect, and the risk of shortage of per capita resources in a given planning period. Therefore, it is important to integrate different risks into an urban FEW system, including the risk of systematic impact (e.g., fluctuating resource demand and resource availability, disruption in supply chain, etc.) and potential cascade effect (natural disaster, climate vulnerabilities, etc.) (Howarth & Monasterolo, 2016). Most importantly, the associated risks of adopting different technologies in different resource systems are intimately tied to carrying out the potential tradeoffs and retaining synergies. Therefore, based on the principles (discussed in relation to the technology hubs in Section 4), the potential risks of technology integration for different resources systems should be assessed critically in future FEW systems.

Different techniques and tools have differing limitations given their data collection and data quality concerns. Table 1 highlights some of the recent tools and techniques used in different nexus applications with their strengths, weaknesses, and limitations. However, recent advances in computational and algorithmic simulation, multilevel programing, and integration of LCA can help solve issues with complex and large-scale FEW systems to provide effective planning and policy decisions (Garcia & You, 2016). By considering the existing databases, software tools, and the feasibility of its adoption, LCA can be a key tool for FEW nexus assessments (Salmoral & Yan, 2018). As there is no standardized methodology for quantifying the environmental benefits of an urban FEW nexus system, an integrated LCA method along with other nexus tools is essential for determining environmental impacts and possible benefits for different scenarios (Mannan et al., 2018). In addition, heuristic algorithms can be integrated for optimization solvers, GIS for spatial analysis of resources, sensing systems for real-time data collection, system dynamics for the flow of resources and graphical representation, predictive modeling for scenario analysis with respect to different policies, and so on, leading to comprehensive FEW evaluations.

It is not easy to delineate the boundary of sustainability assessment to enhance sustainable development (Das & Cabezas, 2018). Case studies containing all relevant factors in FEW systems are very limited. Scenario analysis with future prediction (long-term) is still lacking in the integrated

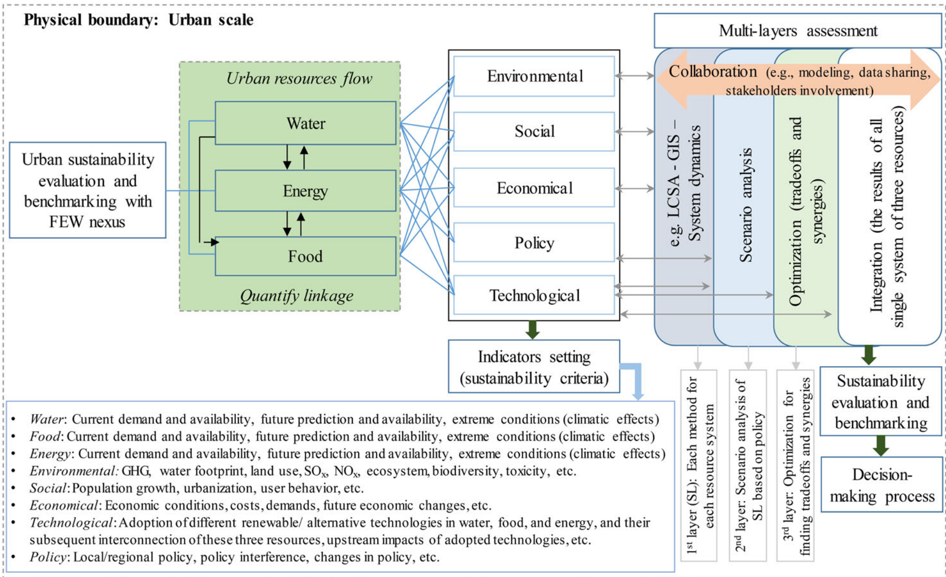

Figure 13. Integrated framework for the assessment of an urban FEW nexus to achieve GREATS urban development.

modeling analysis (Dai et al., 2018). With the exception of carbon and water footprint, no sustainability indicators, such as ecosystem footprint, were fully developed for different FEW nexus analyses. Water and energy sectors are still the priority areas in the current literature, with less focus on the food sector. Incorporating policy and governance paradigms into these FEW systems is still uncommon (Artioli et al., 2017). However, energy generation and consumption are directly related to resource depletion and other environmental impacts (Ng et al., 2014; Lee et al., 2017), and these upstream impact categories should be incorporated into sustainability indicators of the FEW nexus through a holistic risk assessment. Thus, interdisciplinary research coupling these three sectors should be conducted cohesively with case studies of regional significance with respect to different policies and governance structure. Developing multiscale, multiuncertainty, multisector, and multiagent models that incorporate multiple impacts is essential for addressing multiple externalities and exploring recognized challenges. Multi-sectoral systems analysis, a research tool for decision-making, supporting policy and investment could be effective in urban FEW nexuses, as this systematically analyzes the magnitude of material and energy flows and transformation from an urban metabolism perspective (Walker et al., 2014). Based on the applied systems analysis, this paper finally proposes a closing remark via an integrated evaluation framework for an urban FEW nexus to achieve Green, Resilient, Empowering, Adaptable, Transformative, and Sustainable (GREATS) urban development (Figure 13). In this framework, flows of the three most valuable resources can be quantified within a designated physical boundary of varying scales in the first layer of assessment, located at the multilayer building block at the upper right corner of Figure 13. Selected sustainability criteria and indicators are highlighted, along with multilayer evaluation methods for each indicator of different aspects (e.g., environmental, social, economic, and technological aspects) of the proposed FEW systems. Although it requires plenty of data collection, LCSA can be used for the aspects of each of the three FEW nexus pillars to assess the sustainability performance with the aid of spatial analysis techniques. These spatial analysis techniques (i.e., Geographical Information System) can be linked with system dynamics models from which the urban growth models at large can be applied for intertwined material and energy flow analyses via urban growth visualization. These interlinkages for formalizing the multiscale, multiuncertainty, multisector, and multiagent models can serve as a neural system in the applied systems analysis.

In the second layer of assessment, the findings of the first layer can be analyzed based on different policy or planning scenarios according to changes of policy and /or technology adoption. In the third layer of assessment, cost-benefit-risk tradeoffs using optimization models or multiagent models can be highlighted for managing complexity and enhancing synergies based on the findings of the second layer. Finally, the results of all individual systems analyses of the three sectors can be integrated for sustainability assessment and benchmarking in terms of water, carbon, and ecosystem footprint for selected scenarios.

The results can also be supportive in a policy analysis and governance decision-making process to justify the legitimacy of policy/law and regulations in relation to the FEW systems. However, collaborations with different stakeholders are needed for data collection, and with experts for different modeling and analysis. Although the proposed framework is mainly based on an urban scale, it can be enlarged into a national and global scale as local/regional FEW systems are interconnected by local resources and can impact national and international markets as well (Kling et al., 2017).

4. Conclusions

This thorough review reveals the contemporary themes and issues of FEW nexus that help identify the niche of possible technological advancement for different urban FEW systems with respect to changing environmental, economic, and social contexts. In total, 90 scientific articles were systematically analyzed to map out the challenges and limitations of existing FEW nexuses with some case studies. This effort led to the identification of the spectrum of nexus considerations, nexus priority issues, sustainability indicators, models, methods, frameworks, and tools, toward future perspectives. Moreover, several recently used nexuses across three countries (United States, Netherlands, and France) were critically and collectively analyzed and compared in terms of tools, nexus scope, integration, and limitations to highlight the potential of innovative FEW systems in different socioeconomic and cultural contexts. Moreover, sustainability assessment of such nexus systems may be compared by addressing multifaceted challenges, where the integrated framework of GREATS can be adopted for advanced systems analysis to achieve better urban development.

Overall, although great progress has been made by individual studies, the practical implementation of integrated urban FEW nexuses is still limited across the globe. Issues of alternatives prioritization, indicators selection, scenario planning, and tradeoffs are yet to be fully assessed over the three sectors. The water-energy nexus is still a priority focus without critically considering its relationship with the food sector. Interdependence and interconnection among the FEW sectors were rarely confirmed and analyzed in the case studies of the reviewed literature. Cases of integrated assessment for predicted performance integrating both present, past, and future policy actions based on both bottom-up and top-down approaches are still lacking. There is an acute need for integrative thinking and transdisciplinary approaches to address these large-scale and complex FEW systems. Although several tools for FEW nexus assessments are available, the improvements in data collection and sharing, model calibration and validation, as well as uncertainty analysis, are also desperately needed to fully realize the complexity embedded in multiscales, multiagents, multisectors, and multiimpacts. Future studies should advance the understanding of FEW systems from the perspective of system of systems engineering in terms of different paired sectors or extended sector structure with respect to differing indicators, evaluation criteria, tools, methodologies, etc., and innovate the analytical strategies via top-down or bottom-up approaches with cascade effects across scales to sort out the nature of different interconnected and interdependent complex FEW systems scientifically.

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