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TOPICAL REVIEW

The Water-Energy-Food Nexus: A systematic review of methods for nexus assessment

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Abstract

The water-energy-food (WEF) nexus is rapidly expanding in scholarly literature and policy settings as a novel way to address complex resource and development challenges. The nexus approach aims to identify tradeoffs and synergies of water, energy, and food systems, internalize social and environmental impacts, and guide development of cross-sectoral policies. However, while the WEF nexus offers a promising conceptual approach, the use of WEF nexus methods to systematically evaluate water, energy, and food interlinkages or support development of socially and politically-relevant resource policies has been limited.

This paper reviews WEF nexus methods to provide a knowledge base of existing approaches and promote further development of analytical methods that align with nexus thinking. The systematic review of 245 journal articles and book chapters reveals that (a) use of specific and reproducible methods for nexus assessment is uncommon (less than one-third); (b) nexus methods frequently fall short of capturing interactions among water, energy, and food—the very linkages they conceptually purport to address; (c) assessments strongly favor quantitative approaches (nearly three-quarters); (d) use of social science methods is limited (approximately one-quarter); and (e) many nexus methods are confined to disciplinary silos—only about one-quarter combine methods from diverse disciplines and less than one-fifth utilize both quantitative and qualitative approaches.

To help overcome these limitations, we derive four key features of nexus analytical tools and methods—innovation, context, collaboration, and implementation—from the literature that reflect WEF nexus thinking. By evaluating existing nexus analytical approaches based on these features, we highlight 18 studies that demonstrate promising advances to guide future research. This paper finds that to address complex resource and development challenges, mixed-methods and transdisciplinary approaches are needed that incorporate social and political dimensions of water, energy, and food; utilize multiple and interdisciplinary approaches; and engage stakeholders and decision-makers.

1. Introduction

We are confronted with the challenge of effectively managing resources to better achieve sustainable outcomes, such as those emphasized by the global community in the Sustainable Development Goals (SDGs, UN 2015). In recent years, the water-energy-food (WEF) nexus has taken center-stage as a way to better understand complex interactions among multiple resource systems. Thus far, however, specific methods to analyze WEF interactions and address complex resource and development challenges remain limited.

Use of the WEF nexus concept is rapidly expanding in scholarly literature and policy settings (Keairns *et al* 2016). Here, we understand the WEF nexus as a systems-based perspective that explicitly recognizes water, energy, and food systems as both interconnected and interdependent (Bazilian *et al* 2011, Wolfe *et al* 2016, Foran 2015). By considering how water, energy, and food systems operate and interact, the nexus approach aims to maximize synergies (mutually beneficial outcomes) and minimize trade-offs (which may potentially include non-optimal outcomes), improve resource-use efficiency, and internalize social and environmental impacts, particularly across a range of contexts and scales (Kurian 2017). The underlying aims are to strengthen cross-sectoral integration and improve management outcomes to enhance water, energy, and food security (Scott *et al* 2016).

While the WEF nexus originally focused on clarifying interlinkages between physical resource systems (Webber 2016), further refinements of the nexus concept recognize the need to incorporate environmental, economic, political, and social dimensions (Lawford *et al* 2013). For example, de Grenade *et al* (2016) situate the nexus among interacting social and physical systems, while Biba (2016) argues that political dimensions of water, energy, and food systems are key to achieving nexus goals. To achieve sustainable outcomes, WEF nexus approaches need to evaluate nexus impacts on human livelihoods and the contribution of institutions for improving resource governance, particularly at the community level (Biggs *et al* 2015). In addition to understanding tradeoffs and resource-use efficiency among physical systems, how water, energy, and food resources are governed affects outcomes in terms of social equity, externalities, and socio-ecological resilience (Scott *et al* 2015). Nexus analyses are often conducted at regional or national levels due to the availability of data or national-level policy goals or metrics (Miralles-Wilhelm 2016), however a balance of top-down and bottom-up approaches are needed to address multiple scales of interactions (Chang *et al* 2016). Although conceptualizations of the WEF nexus have become increasingly complex, incorporating a plurality of drivers and dimensions, there has been less rapid development and use of nexus analytical approaches to assess and analyze WEF interactions (Foran 2015, Chang *et al* 2016).

Existing nexus methods excel in specific applications (e.g. integrated modeling for physical resource tradeoff evaluation), however calls abound for nexus-specific methods that better represent cross-sectoral social, environmental, and technical challenges (Keairns *et al* 2016, FAO 2014, Smajgl *et al* 2016) and that incorporate the social, political, and institutional context of water, energy, and food sectors (Allouche *et al* 2015, Foran 2015). Many nexus studies focus on dual-sector interactions, e.g. water-food or water-energy. Because of the water-centric nature of the nexus in many studies, researchers have found that 'current Nexus analyses are insufficiently cross-sectoral' (Smajgl *et al* 2016: 533) to improve coordination of policies across resource sectors and reduce unintended tradeoffs and impacts among water, energy, and food security, all key elements of the sustainable development agenda. To identify, understand, and analyze interconnections and interdependences among water, energy, and food systems, there is a need for all three sectors to be considered together, and equally, through an integrated analysis (Chang *et al* 2016, Miralles-Wilhelm 2016, Smajgl *et al* 2016). Integrated analytical approaches that address the complexity of the three-pronged nexus may identify cross-sectoral tradeoffs and internalize driving forces that might otherwise be overlooked in dual-sector approaches (Miralles-Wilhelm 2016). Furthermore, the complexity of developing cross-sectoral management and policies demands attention to the sociopolitical context of these systems (Allouche *et al* 2015, Foran 2015). Given the need to advance integrated analytical approaches to study WEF systems and support cross-sectoral integration, this article focuses on reviewing existing methods used in WEF nexus studies.

Previous studies have discussed subsets of nexus tools (e.g. FAO 2014), yet despite the increasing use of the WEF nexus in scholarly literature and policy settings, few studies have systematically reviewed the broad range of methods employed in the body of nexus literature. There is need for a comprehensive review of, and critical reflection on, existing nexus methods to identify best practices, improve accessibility, and promote further advances in methods for nexus assessment (Keairns *et al* 2016).

This paper reviews current WEF nexus analytical approaches to promote further development of tools and methods that align with nexus thinking and address the complexity of multi-sectoral resource interactions. 'Nexus thinking' emphasizes the inherent links among water, energy, and food resource systems and aims to overcome single-sector approaches to resource governance (World Economic Forum 2011, Biggs *et al* 2015). As described by Keskinen *et al* (2016: 3), the WEF nexus can serve in multiple roles—as an analytical tool, a conceptual framework, or a discourse. As an analytical tool, a nexus analysis systematically uses quantitative and/or qualitative methods to understand interactions among water, energy, and food systems. However, the nexus has remained largely in the conceptual domain (Smajgl *et al* 2016). As a conceptual framework, the nexus approach leverages an understanding of WEF linkages to promote coherence in policy-making and enhance sustainability. Finally, as a discourse, the nexus concept can be used for problem framing and promoting cross-sectoral collaboration (Keskinen *et al* 2016: 3). Herein, we consider the various tools and methods utilized analytically for nexus assessment. We refer to such tools (e.g. quantitative models) and methods (e.g. participatory stakeholder workshops) generally as *analytical approaches,* or specifically as *methods or tools.*

We begin by situating the WEF nexus in its historical and global policy context (section 1). Section 2 describes the criteria used to select articles for our systematic review of WEF nexus methods and how these articles were analyzed. Next, in section 3, we present our findings that characterize the diversity of nexus

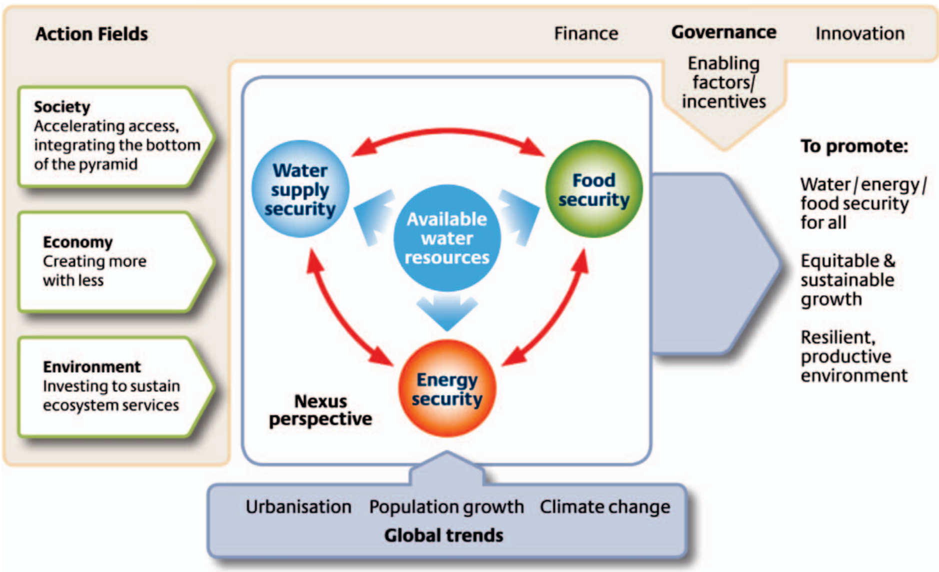

Figure 1. Water-Energy-Food Security Nexus from Hoff (2011). Source: Understanding the Nexus: Background paper for the Bonn 2011 Nexus Conference, Stockholm Environment Institute 2011. Reprinted with permission.

methods in the reviewed articles and derive key, normative features of analytical tools and methods from the body of WEF nexus literature. We then analyze existing nexus methods based on their contributions in these key areas—degree of innovation, influence of context, degree of collaboration, and ability to address policy needs or implement methods in practice. These key areas are further defined and described in sections 2 and 3.3. In section 4, we identify and highlight 18 studies that demonstrate nexus methods that are well-aligned with nexus thinking. Our findings bring to the forefront the need for new nexus-specific methods that advance our understanding of multi-sectoral interactions, system externalities, and sustainable outcomes. To support further development of robust nexus methods, we highlight examples of analytical approaches that explicitly address the sociopolitical context, combine quantitative with qualitative data to advance interdisciplinary and mixed methods, and deeply engage with stakeholders and decision-makers. Such approaches provide a way forward for advancing nexus assessments that promote socially and politically-feasible outcomes, as discussed in section 5.

1.1. The water-energy-food nexus on the global stage

We focus our analysis on the conception of the nexus as the linkages and interactions among water, energy, and food systems (WEF). The WEF nexus has a relatively compressed history and evolution, as reviewed by Scott *et al* (2015). The rapid spread of green-revolution agriculture, especially in intensively irrigated breadbasket regions (e.g. Punjab in South Asia, Central and Northwest Mexico, and the Ogallala Aquifer area of the central US), and the subsequent recognition of groundwater-mining for food production (e.g. Jordan Valley and Disi Aquifer in Saudi Arabia) highlighted the interactions among energy and water for agricultural production and food security and gained scholarly attention.

Following initial attention in scholarly research and practice, reports by Hoff (2011) and World Economic Forum (World Economic Forum 2011) were pivotal in moving the WEF nexus concept into the limelight of global institutions. The timing and institutional provenance of both were strategically important. Hoff (2011) was prepared as a concept piece for the Bonn2011 Nexus Conference; its main contributors included international policy think-tanks, agencies of the United Nations (UN) and the German Federal Government, and crucially, global finance bodies. This effort was admittedly conceptual, referring to water, energy, and food in relation to ecosystem services, urbanization, globalization, the expanding discourse on security, and with dual development objectives to strengthen poverty alleviation and the green economy (figure 1). Hoff (2011) proved a significant step in establishing the nexus concept and remains one of the most widely cited reports on the WEF nexus.

The second high-impact report on the nexus by the World Economic Forum (World Economic Forum 2011) aimed to strengthen global financial institutions' investments in the provision of water, energy, and food as resources for human use. This conceptual framework focused on nexus linkages as they related to water, energy and food security (figure 2). Governance of these three strategic resources, as well as climate adaptation, occurs principally in the public domain. By contrast, investment, profits, and losses in the private sector were recognized by the World Economic Forum (2011) to represent the windfall opportunity of

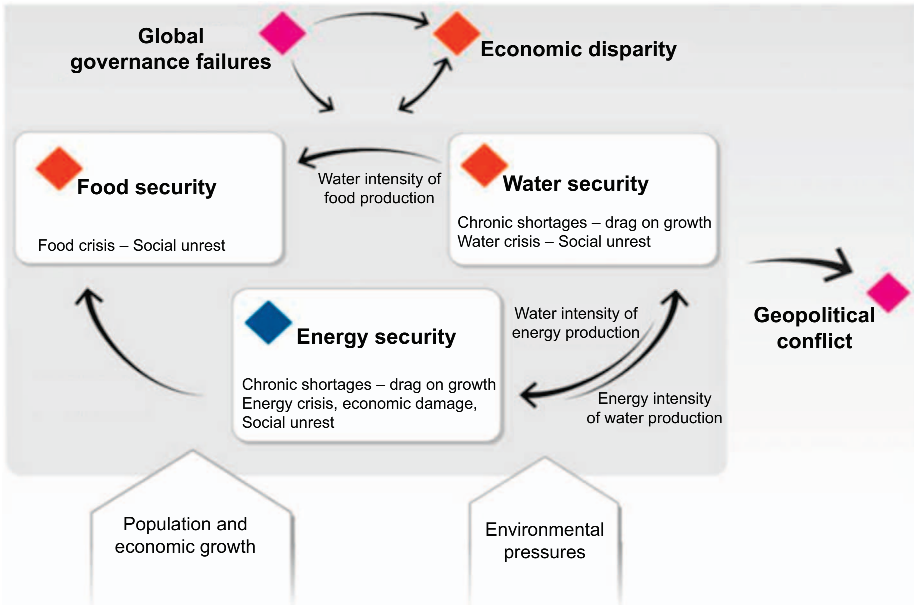

Figure 2. Water-Energy-Food Security Nexus from World Economic Forum. Source: Global Risks 2011 (Sixth Edition), World Economic Forum, Switzerland, 2011. Reprinted with permission.

current times. This built on recognition of water and energy infrastructure needs that had been identified by the World Economic Forum in 2008 (World Economic Forum 2008). The 2011 World Economic Forum report features position statements of key representatives of governments, UN agencies, international NGOs, multilateral and national public finance institutions, and a large number of private businesses (commodity sales, product lines, entrepreneurs, etc.).

Following publication of these pivotal reports, efforts to develop a knowledge base and strategies for applying nexus thinking received increasing attention in research, development, and policy. Much of this discussion has taken place in reports and other grey literature (e.g. in publication outlets for which formal peer-review is not required). While the systematic review we present in this paper focuses on the peer-reviewed literature, our review builds on reports from the grey literature that have proposed or assessed WEF nexus methods in detail (e.g. Granit *et al* 2013, IRENA 2015, LIPHE4 2013, RAND Corporation 2016). Most notable is FAO (2014), which calls for formal assessments based on quantitative analysis, application of tools, and comparison of various interventions. The WEF nexus has been applied to analyze particular resource issues, including irrigation, ethanol production, hydropower, forestry, desalination, and bioenergy. Indicators, benchmarks, and tools are reviewed and collated in the FAO report. Case studies utilizing tools and methods developed in the grey literature are often reported in peer-reviewed articles. We include multiple such articles in our review. For example, de Strasser *et al* (2016) employ a methodology developed by the United Nations Economic Commission for Europe (UNECE 2015).

In research, policy, and practice, the nexus has only partially lived up to its potential to identify and minimize tradeoffs at the level of resource use and production. However, the nexus approach in this context has expanded from a set of input-output relationships to a broader footprint understanding in which the implications of energy consumption for carbon mitigation and climate adaptation have gained credence. Recent research on the WEF nexus addresses food commodity chains, including transport and cooling, end-consumers, and waste and effluent management (e.g. Vlotman and Ballard 2014, Villarroel Walker *et al* 2014). WEF nexus studies also contribute conceptual accounts for tradeoffs inherent in decisions to grow crops for biofuels or for food (e.g. Moioli *et al* 2016). Such expanded conceptualization has not been accompanied by coordinated development of a comprehensive set of tools and methods for analysis and quantification. Instead, methods have largely been borrowed or adapted from conventional disciplinary approaches, e.g. efficiency analysis based on engineering process studies, economic supply-chain and commodity-chain analyses, and agronomic soil-plant-water assessments. These approaches provide a narrow perspective of water, energy, and food interactions, with limited ability to capture the interconnections and interdependencies among the multi-sectoral systems, thus perpetuating a fractured view of the three-pronged WEF nexus.

Nexus thinking is not appropriate for all contexts and problems. However, where a WEF nexus perspective helps address water, energy, and food resource challenges, robust analytical approaches can enhance the provision of multi-sectoral nexus solutions, in the form of integrated policy, cohesive community decision-making, maximization of resource-use synergies, and sustainable outcomes achieved through socially and politically-feasible strategies.

2. Methods

We searched the Scopus database for keywords '*water*', '*energy*', '*food*', and '*nexus*' in the abstract, title, and keywords of the database articles. We searched only peer-reviewed journal articles in the English language published through 2016. The Scopus search resulted in 221 documents[4]. Recognizing the limitations of this search method (e.g. that all nexus studies may not use these specific terms), we also looked for articles that used alternative language, such as irrigation, electricity, and agriculture, or that used our search terms outside of the abstract, title and keywords to obtain an additional 24 articles (e.g. by snowball sampling). Thus, a total of 245 articles were identified. Although selected articles were limited to peer-reviewed works, tools and methods for nexus applications originally developed by non-governmental or inter-governmental research and policy institutes (e.g. SEI, FAO, UNECE) are applied and tested in many of the selected works (e.g. de Strasser *et al* 2016, Karlberg *et al* 2015).

Articles were selected based on the following criteria: (1) they explicitly employ the nexus concept in terms of natural resources sustainability; (2) they meaningfully include all three resource sectors: water, energy, and food; and (3) they test or propose specific analytical tools for evaluating the nexus. Articles that met only the first two criteria, but did not explicitly propose or test analytical tools, were categorized as 'conceptual'. Of the 245 articles identified, 25 articles (10%) were classified as 'conceptual', 73 articles (30%) were classified as 'methodological', and 147 articles (60%) were excluded.

To ensure consistency of our review methods, articles were excluded if they did not meet any of the selection criteria. For example, some articles did not engage with natural resources sustainability and included the 'nexus' as merely a buzzword. Although the mention of all three sectors was common, we excluded articles that only analyzed resource nexus interactions between two sectors, for example, focusing solely on water–energy interactions (see Endo *et al* 2017 for a typology of the literature). Here we focus on the three-pronged nexus (at a minimum) because addressing water, energy, and food systems is inherently more complex than a two-pronged nexus and therefore, analytical approaches for assessing the WEF nexus need to consider this added complexity. Finally, because a key aim of our analysis was to support the further development of robust nexus methods, we also excluded papers that did not test or propose specific analytical tools for evaluating the nexus.

We coded the subset of 73 'methodological' articles for information related to publication (e.g. journal, year, journal discipline) and nexus methods (e.g. single discipline, interdisciplinary, qualitative, quantitative, or both). We also examined (a) if the articles were claiming a 'new' method, combining multiple methods within a discipline, or using a single method; (b) if the articles showed a preference for a certain sector; (c) if there was a case study; (d) what the purpose or end-goal of the study was; (e) what the scale of analysis was; and (f) major challenges or limitations in the application of nexus method(s). Next, we conducted a quantitative analysis of trends and characteristics of nexus methods reported in the literature (e.g. number of publications over time, diversity of disciplines, utilization of quantitative or qualitative approaches).

We reviewed all 25 'conceptual' articles to glean what data gaps, research needs, and normative attributes were called for in relation to nexus tools and methods. We refer to these normative attributes of nexus methods identified in the literature as 'key features' of nexus methods. These key features describe desirable qualities such as how methods help approach nexus analysis, what information and data are included or excluded, how interdisciplinary interactions are treated, and who is involved in the research.

We also compiled prescriptions for features of nexus methods or research needs from the 'methodological' articles, where applicable. From this review, based on more than 35 publications, we derived a set of four key features for nexus analytical approaches—innovation, context, collaboration, and implementation—as discussed in section 3.3. We then evaluated stated methods from the 73 'methodological' articles according to these four key features in a second round of coding. Innovation included methods that worked to address the complexity of nexus interactions such as understanding WEF linkages, system dynamics, system boundaries in new and novel ways. Context included methods that sought to understand the historical, social, political and/or economic dynamics of WEF systems as well as those that aimed to capture multi-scalar system dynamics and were flexible or adaptable to different or changing conditions. Collaboration included methods that encouraged broad participation and cooperation from different sectors. Examples of such methods included inter-, multi-, or trans-disciplinary approaches as well as methods that aimed to improve data-sharing. Implementation included methods that sought to be applied in practice by being accessible to decision-makers, addressing policy-relevant questions, and offering a systematic process to employ the method(s) in practice. Recognizing the challenges of coding methods based on

[4] Scopus has a greater journal coverage for all fields compared to other databases commonly used in research (e.g. Web of Science). However, the Scopus database provides somewhat better coverage of natural science, engineering and biomedical journals compared to social sciences, arts and humanities, and favors English-language journals (Mongeon and Paul-Hus 2016). To mitigate these limitations, we also conducted snowball sampling.

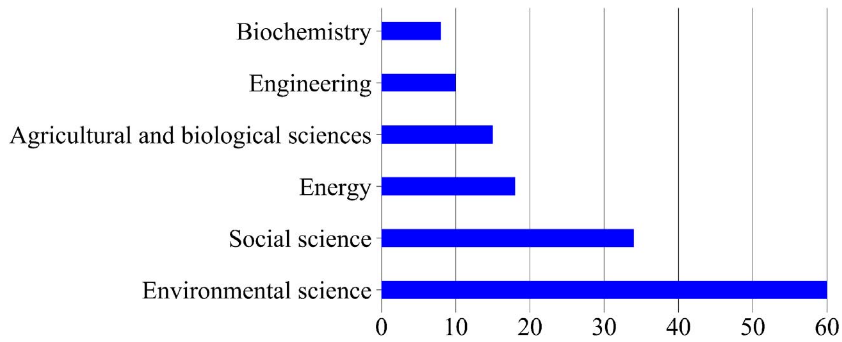

Figure 3. Number of articles published in a journal categorized under the disciplines listed. For example, 60 of the articles reviewed were published in a journal categorized in the 'Environmental sciences.' Most journals are listed in more than one category; thus, the totals of all categories exceed the total number of articles. Other categories not shown in the figure were mentioned less than five times each: 'Business', 'Chemical engineering', 'Medicine', 'Computer science', 'Psychology', 'Nutrition', 'Economics', 'Earth and planetary sciences' and 'Decision sciences'. One journal was not categorized in Scopus.

a broad classification, we focused on the language describing methods in the 'methodological' articles to guide our classification of reviewed methods. We then identify and highlight 18 studies whose methods address multiple key features identified in the literature as research needs and offer examples of promising nexus approaches. The 18 studies as well as the key features of nexus analytical approaches, are discussed further in sections 3.3 and 4.

3. Characterizing nexus methods

Our review reveals that explicit and reproducible methods to assess water, energy, and food systems together are limited. Only 30% of peer-reviewed literature reviewed (73 of 245 articles) present nexus methods or propose specific analytical tools. Those without explicit methods instead utilize the nexus as a conceptual framework or offer descriptive accounts of water, energy, and food systems.

Despite the lack of nexus methods presented in the 245 articles reviewed, analytical approaches to assess WEF nexus are emergent and growing. The remainder of section 3 presents results based on analysis of the subset of 'methodological' articles (n = 73) that offer specific methods for nexus assessment. These include articles published through the end of 2016, however, more than three-quarters (81%) were published in 2015 or 2016.

Coinciding with the increase in the use of the WEF nexus as an analytical tool, we found WEF nexus methods have been widely published—37 different journals are represented spanning a broad range of disciplines. Of the articles reviewed, approximately 36% (26 articles of 73 total) were published in journals focused on the water sector (e.g. hydrology, water resources, and water policy). Studies were most often published in journals from the fields of environmental sciences, social sciences, energy, and agricultural, and biological sciences (figure 3), generally consistent with findings by Keairns *et al* (2016). Most journals cover more than one discipline (per categories defined in the Scopus database).

Although we only selected articles that meaningfully considered all three sectors—water, energy, and food—our review of the selected articles revealed more than half (55%) showed some preference for one sector, either in terms of framing the analysis or the discipline from which the methods used are derived. Preference was most commonly given to the water sector (21% of the total), which reflects the close relationship of the origin of the nexus concept to water security and integrated water resources management. Less than 10% focused more so on either the energy or food sectors (8% and 7%, respectively), while 19% prioritized two of the three sectors.

3.1. Diversity of nexus methods

Analytical approaches for evaluating the WEF nexus are derived from various disciplines. Our review revealed that numerous and diverse analytical tools have been used or proposed for examining the WEF nexus and many studies combined multiple methods. Methods that originate from the fields of environmental management and economics were most commonly utilized (figure 4). Methods from the field of environmental management were used in 60% of studies (44 of 73); economic tools were used in 45% of studies (33 of 73). We also discovered a broad range of social science methods (e.g. institutional analysis, Delphi technique, agent based modeling, participatory workshops), at least one of which was utilized in 26% of studies (19 of 73). We tabulated and categorized WEF nexus tools and methods from all 73 'methodological' papers based on discipline and/or type of method in table 1.

Methods used or proposed most often drew from existing disciplinary techniques. Most studies utilized

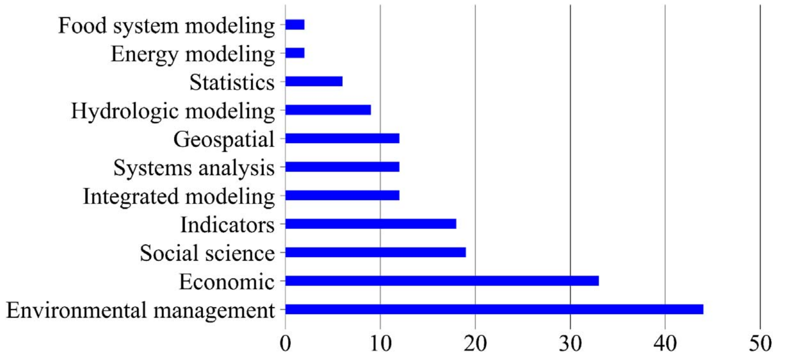

Figure 4. Number of articles using one or more method from each category. Many studies used more than one method, thus total methods exceed the total number of studies reviewed.

multiple tools, though these were often closely related. Approaches most commonly featured a combination of tools from the areas of environmental management, economics, indicators, statistics and integrated models. Specific tools frequently used include life-cycle assessment, input-output analysis, tradeoff analysis, footprinting, or integrated models with scenario analysis. For example, input-output analysis or tradeoff analysis from the field of economics is often paired with scenario assessment. Alternatively, other studies integrated data from multiple sectors while using a single approach for analysis, e.g. via computational modeling. For example, integrated physical models combine hydrologic, agricultural, energy and climate data.

Approaches that combine tools or methods from disciplines with disparate epistemologies are much less common (27%). For example, some studies pair policy analysis with tradeoff analysis (Smidt *et al* 2016) or policy analysis with water balance modeling (Scott 2011); others combine hydrologic models with spatial analysis of demographic data and participatory scenario analysis (Keskinen *et al* 2015). We found a preference for quantitative methods—70% of studies used primarily quantitative approaches. Less than one-quarter (19%) used quantitative and qualitative methods together, such as interview data and quantitative footprinting analysis (e.g. Cottee *et al* 2016). Only 10% relied on qualitative methods alone.

Further, few new tools or methods have been developed specifically to address WEF nexus linkages. Examples of such new tools include integrated modeling platforms designed specifically to address water, energy, and food interactions (e.g. Bekchanov and Lamers 2016); economic functions devised to identify optimal tradeoffs among water, energy, and food production and use (e.g. Perrone and Hornberger 2016); and, interdisciplinary approaches that incorporate participatory workshops and dialogues with stakeholders (e.g. de Strasser *et al* 2016).

The diversity exemplified in the catalog of WEF nexus methods (table 1) provides a strong foundation for further development of nexus methods. While a detailed description of each tool or method listed in table 1 is beyond the scope of this paper, table 1 is provided to direct researchers and practitioners to examples of studies that cumulatively offer a breadth of analytical approaches from diverse disciplines[5].

Previous works include detailed descriptions of many of these disciplinary tools, as described in table 2. For example, Keairns *et al* (2016) review quantitative approaches including life-cycle analysis and integrated models, and Semertzidis (2015) reviews tools developed for the energy sector. We build on these earlier reviews to advance nexus methods toward more integrative and comprehensive techniques.

3.2. Underlying reason studies employ a nexus approach

In the 73 articles we reviewed, we discovered that a nexus approach was utilized to address multi-faceted aims. By reviewing the stated aims for employing a nexus approach, we found that studies most commonly sought to improve resource-use efficiency or management, enhance policy integration, and/or promote sustainable resource-use practices (figure 5). Resource-use efficiency or management and policy integration were cited in more than half of the studies reviewed, and sustainability was mentioned in nearly one-half. Resource-use efficiency and effective management is regarded as the outcome of considering synergies and trade-offs among water, energy, and food sectors (De Laurentiis *et al* 2016, Giupponi and Gain 2016) and optimizing inter-sectoral linkages (Endo *et al* 2017). A nexus approach was also employed to improve decision-making when dealing with complex systems (Pittock *et al* 2016) and

[5] For definitions and descriptions of these methods, the reader is directed to Belcham 2015, Given 2008, Lewis-Beck *et al* 2004, Salkind and Rasmussen 1981 and the references listed in table 1.

Table 1. Catalog of WEF nexus methods used in the sample set, categorized by discipline. The number of studies and the percentage of total studies ($n = 73$) that utilized at least one method from each discipline-based grouping is summarized in bold subheadings. Many studies used more than one method; thus, percentages listed by category do not add to 100%. The number of studies utilizing each method is summarized in the first column, following the method name. Citations are provided for specific methods used. For methods used by more than five studies, we underline citations to direct the reader to prominent examples that demonstrate each method.

Environmental management	**44 studies (60%)**
Scenario analysis (25)	Al-Ansari *et al* 2015, Bonsch *et al* 2016, Bowe and van der Horst 2015, Daccache *et al* 2014, Daher and Mohtar 2015, Damerau *et al* 2016, Haie 2015, Jalilov *et al* 2015, 2016, Karlberg *et al* 2015, Keskinen *et al* 2015, Martin-Gorriz *et al* 2014, Perrone and Hornberger 2016, Ringler *et al* 2016, Scott 2011, Smajgl *et al* 2016, Topi *et al* 2016, van Vuuren *et al* 2015, Villarroel Walker *et al* 2012, 2014, Walsh *et al* 2016, Welsch *et al* 2014, Wolfe *et al* 2016, Yang *et al* 2016a, 2016b
Footprinting (13)	Cottee *et al* 2016, Daccache *et al* 2014, Damerau *et al* 2016, Elbehri and Sadiddin 2016, Heckl *et al* 2015, Irabien and Darton 2015, Kajenthira Grindle *et al* 2015, Lacirignola *et al* 2014, Pacetti *et al* 2015, Roibás *et al* 2015, Rulli *et al* 2016, Talozi *et al* 2015, Vlotman and Ballard 2014
Life cycle assessment (8)	Al-Ansari *et al* 2015, De Laurentiis *et al* 2016, Irabien and Darton 2015, King and Carbajales-Dale 2016, Pacetti *et al* 2015, Pradeleix *et al* 2015, Ravi *et al* 2016, Scott and Sugg 2015
Stakeholder engagement (2)	Haie 2015, Howarth and Monasterolo 2016
Decision support (2)	Wolfe *et al* 2016, Yang *et al* 2016b
Benefit analysis (2)	Olsson *et al* 2015, Soliev *et al* 2015
Economic	**33 studies (45%)**
Input-output analysis (14)	Bowe and van der Horst 2015, Daher and Mohtar 2015, Haie 2015, Kajenthira Grindle *et al* 2015, King and Jaafar 2015, Li *et al* 2013a, Li *et al* 2016, Martin-Gorriz *et al* 2014, Olsson *et al* 2015, Pacetti *et al* 2015, Perrone and Hornberger 2016, Scott and Sugg 2015, Sharma *et al* 2010, Zimmerman *et al* 2016
Cost-benefit analysis (1)	Endo *et al* 2015
Tradeoff analysis (10)	Bonsch *et al* 2016, Daher and Mohtar 2015, Hurford and Harou 2014, Mayor *et al* 2015, Perrone and Hornberger 2016, Rulli *et al* 2016, Scott and Sugg 2015, Smidt *et al* 2016, van Vuuren *et al* 2015, Xiang *et al* 2016
Social accounting matrix (1)	Doukkali and Lejars 2015
Economic modeling (including econometric modeling, dynamic panel modeling, etc.) (6)	Damerau *et al* 2016, Endo *et al* 2015, Hurford and Harou 2014, Ozturk 2015, Ringler *et al* 2016, Topi *et al* 2016
Value chain analysis (2)	Roibás *et al* 2015, Villamayor-Tomas *et al* 2015
Supply chain analysis (including process graph framework) (3)	Heckl *et al* 2015, Irabien and Darton 2015, Vlotman and Ballard 2014
Indicators	**18 studies (25%)**
Indicators, metrics or indices (18)	Cottee *et al* 2016, de Strasser *et al* 2016, Elbehri and Sadiddin 2016, Endo *et al* 2015, Giupponi and Gain 2016, Karabulut *et al* 2016, Keskinen *et al* 2015, King and Carbajales-Dale 2016, King and Jaafar 2015, Li *et al* 2016, Martin-Gorriz *et al* 2014, Moioli *et al* 2016, Ozturk 2015, Roibás *et al* 2015, Scott 2011, Stucki and Sojamo 2012, Topi *et al* 2016, Zimmerman *et al* 2016
Statistics	**6 studies (8%)**
Principal component analysis (1)	Ozturk 2015
Regression statistics (3)	Li *et al* 2013b, Sharma *et al* 2010, Topi *et al* 2016
Trend analysis (2)	Xiang *et al* 2016, Yang *et al* 2016a
Social science	**19 studies (26%)**
Institutional analysis (4)	de Strasser *et al* 2016, Sharma *et al* 2010, Soliev *et al* 2015, Villamayor-Tomas *et al* 2015
Questionnaires, surveys, or interviews (8)	Cottee *et al* 2016, de Strasser *et al* 2016, Endo *et al* 2015, Halbe *et al* 2015, Karlberg *et al* 2015, Martin-Gorriz *et al* 2014, Sharma *et al* 2010, Villamayor-Tomas *et al* 2015
Historical analysis (3)	Foran 2015, Guillaume *et al* 2015, Soliev *et al* 2015
Agent based modeling (1)	Smajgl *et al* 2016
Delphi technique (2)	Foran 2015, Smajgl *et al* 2016
Critical discourse analysis (2)	Foran 2015, Stucki and Sojamo 2012
Ontology engineering (1)	Endo *et al* 2015
Stakeholder analysis (3)	de Strasser *et al* 2016, Halbe *et al* 2015, Karlberg *et al* 2015
Participatory workshops/Focus groups (8)	de Strasser *et al* 2016, Halbe *et al* 2015, Howarth and Monasterolo 2016, Karlberg *et al* 2015, Keskinen *et al* 2015, Smajgl *et al* 2016, Villamayor-Tomas *et al* 2015, Wolfe *et al* 2016
Policy analysis (4)	Mayor *et al* 2015, Scott 2011, Sharma *et al* 2010, Smidt *et al* 2016
Integrated modeling	**12 studies (16%)**

Table 1. *Continued.*

Environmental management	44 studies (60%)
Integrated assessment models (other than CLEWS) (6)	Bonsch *et al* 2016, Karlberg *et al* 2015, Ringler *et al* 2016, van Vuuren *et al* 2015, Walsh *et al* 2016, Yang *et al* 2016a
Climate, Land-Use, Energy and Water Strategies (CLEWS) model (2)	Howells *et al* 2013, Welsch *et al* 2014
Hydro-economic modeling (3)	Bekchanov and Lamers 2016, Jalilov *et al* 2015, 2016, Yang *et al* 2016b
Systems analysis	**12 studies (16%)**
Multi-sectoral systems analysis (2)	Villarroel Walker *et al* 2012, 2014
Material flows analysis (3)	Al-Ansari *et al* 2015, Villarroel Walker *et al* 2012, 2014
Systems informatics and analytics (1)	Wolfe *et al* 2016
Causal loop diagrams and system feedbacks (2)	Halbe *et al* 2015, Pittock *et al* 2016
Mathematical/engineering modeling (2)	Leung Pah Hang *et al* 2016, Li *et al* 2016
Resource flows (3)	de Strasser *et al* 2016, Mukuve and Fenner 2015a, 2015b
Network analysis (1)	Zimmerman *et al* 2016
Geospatial	**12 studies (16%)**
Spatial analysis (11)	Daccache *et al* 2014, Endo *et al* 2015, Giupponi and Gain 2016, Guillaume *et al* 2015, Karabulut *et al* 2016, Keskinen *et al* 2015, Mukuve and Fenner 2015b, Scott and Sugg 2015, Sharma *et al* 2010, Smidt *et al* 2016, Talozi *et al* 2015
Remote sensing (2)	Sanders and Masri 2016, Sharma *et al* 2010
Hydrologic modeling	**9 studies (12%)**
Hydrologic modeling (e.g. SWAT, Vmod, WaterGAP, SEAWAT, floodplain modeling) (6)	Endo *et al* 2015, Guillaume *et al* 2015, Karabulut *et al* 2016, Keskinen *et al* 2015, Sharma *et al* 2010, Yang *et al* 2016b
Water management models (e.g. WEAP, IRAS-2010) (3)	Daccache *et al* 2014, Hurford and Harou 2014, Scott 2011
Energy modeling	**2 studies (3%)**
Energy models (2)	Bekchanov and Lamers 2016, Heckl *et al* 2015
Food systems	**2 studies (3%)**
Caloric-demand analysis (2)	Mukuve and Fenner 2015a, 2015b
Source-to-service resource modeling (2)	Mukuve and Fenner 2015a, 2015b

Table 2. Contributions of previous nexus review studies.

Citation	Description of nexus methods covered
Bazilian *et al* 2011	Reviews systems thinking and multi-criteria tools whose boundaries are broadly defined to include water–energy–food nexus topics. Emphasis is placed on integrated assessment models.
Endo *et al* 2017	Reviews a selection of qualitative and quantitative methods that support interdisciplinary and transdisciplinary research approaches for nexus studies. Broadly, these include questionnaire surveys, ontology engineering, integrated maps, physical models, benefit-cost analysis, integrated indices, and optimization management models.
Keairns *et al* 2016	Reviews nexus studies. In terms of methods, covers quality-of-life and product studies, large-scale system models (e.g. WELMM, MESSAGE, MuSIASEM, CLEWS and IMAGE), life cycle and supply chain approaches, data sharing, and scenario analysis.
Semertzidis 2015	Categorizes and reviews top-down and bottom-up modeling approaches relevant to a nexus context. Eight energy, economic, and/or policy-relevant models are discussed in more detail (OSeMOSYS, MARKAL/TIMES, LEAP, GTAP, DynEMo, POLES, PRIMES, and E3ME).

responding to system shocks (Howarth and Monasterolo 2016). Further, nexus approaches were used for 'identifying and eliminating contradictory policies' (Doukkali and Lejars 2015: 422), which is necessary to achieve integrated, and coherent, policies that address interconnected resource sectors. Policy integration and improved coordination among agencies is commonly understood to promote long-term sustainability (e.g. Li *et al* 2013b). Although definitions of the WEF nexus remain ambiguous in the literature, our results indicate that a nexus approach is commonly employed to achieve similar goals.

3.3. Key features of nexus methods

Studies on the WEF nexus frequently acknowledge the need to (a) meaningfully address complex

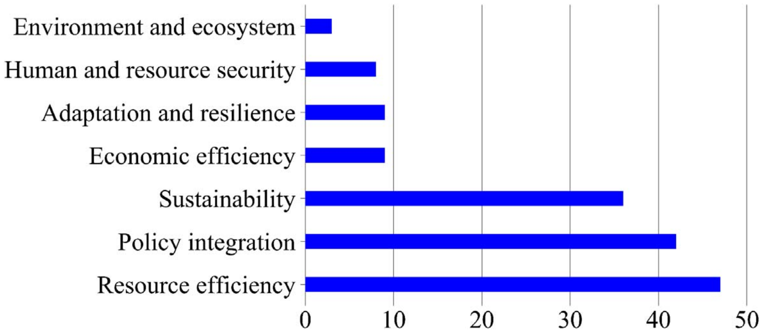

Figure 5. Number of articles stating one or more underlying aims for utilizing a nexus approach. Many studies stated more than one aim; thus total exceeds the total number of studies reviewed. 'Sustainability' includes sustainable resource practices and sustainable development; 'policy integration' includes improving policy- and decision-making, enhancing policy coherence and integration and improving resource governance; 'resource efficiency' includes improving resource use and system efficiency, and resource management. 'Cooperation' and 'social equity' (not shown in plot) were an underlying aim in one study each.

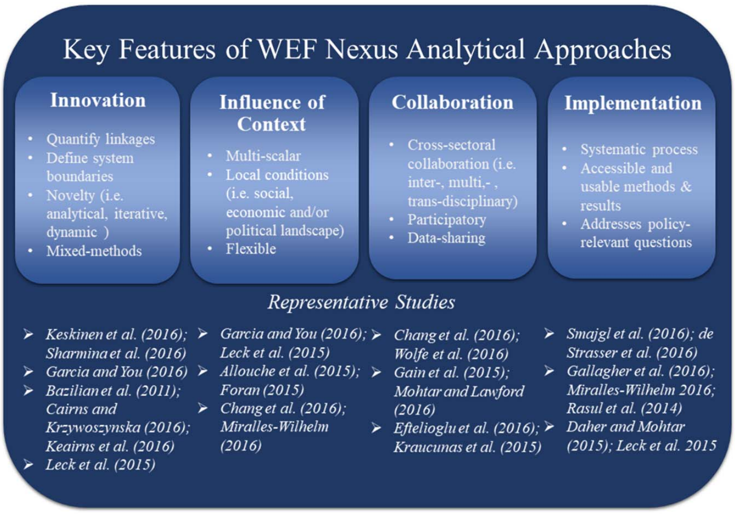

Figure 6. Key features of WEF nexus analytical approaches with corresponding representative studies.

relationships, and interactions and feedbacks among water, energy, and food sectors (e.g. Chang *et al* 2016, Gain *et al* 2015, Smajgl *et al* 2016); (b) incorporate the dynamic context of local conditions (e.g. Foran 2015, Mayor *et al* 2015, Mohtar and Lawford 2016); and (c) produce results usable in policy-making and resource management (e.g. Bazilian *et al* 2011, Guillaume *et al* 2015, Siddiqi *et al* 2013, Wolfe *et al* 2016). However, we found that existing nexus methods and tools have limitations in these areas. While many studies employ multi-sectoral approaches, they often borrow disciplinary tools not specifically designed to evaluate nexus interactions and feedbacks. We found that many studies emphasize quantitative methods that have limited ability to internalize local features—70% of studies utilize quantitative approaches alone. While quantitative approaches are well-suited for evaluating WEF nexus system interactions and tradeoffs, qualitative methods can also offer important contributions to the design and implementation of resource-use policies that are socially and politically feasible (Endo *et al* 2015). There is a stated need for nexus assessment results to be easy to implement, however, few studies incorporate practices that specifically address policy uptake and on-the-ground implementation (e.g. participatory stakeholder engagement; collaborative research; relevant scales of analysis).

Noting the disparity between how robust nexus methods are described in the literature and how methods are implemented in case study assessments, we derived a concise and functional set of key features, or normative attributes, for nexus analytical approaches by synthesizing the recommendations found in the literature (figure 6). The nexus literature calls for methods that address: innovation, context, collaboration, and implementation. The attributes of each of these four key features are broadly discussed below.

3.3.1. *Innovative methods*

New methods and tools are needed to reflect current conceptual framings of the nexus. There is a need to better define system boundaries, quantify and model integrated linkages, and address governance issues (e.g. Keskinen *et al* 2016, Keairns *et al* 2016, Leck *et al* 2015), including the political economy of water, energy, and food systems (e.g. Allan *et al* 2015, Middleton *et al* 2015, Allouche *et al* 2015, Biba 2016). Achieving these goals is no small task. However, there is a foundation of work to build upon. The importance of system boundaries along with their complexity are described in Garcia and You (2016). Because some simplification is always necessary when modeling, how system boundaries are delineated is critical, and should reflect the study aims. Boundaries must be appropriately scaled—large enough to capture the necessarily details, yet small enough to be manageable. Care needs to be given to this process, as boundaries that are far from static shape research assumptions and outcomes (Garcia and You 2016). Reviews by Chang *et al* (2016) and Miralles-Wilhelm (2016) identify limitations in current quantitative approaches to nexus studies—namely how analytical and policy tools are fragmented, focusing on individual sectors, aggregate spatial scales or unrealistically long timeframes—and offer direction for developing robust analytical approaches that aim to tackle the intersection of all three resources: water, energy, and food. Approaches that explicitly focus on interactions and feedbacks are needed. Finally, research is needed that integrates quantitative and qualitative methods in order to achieve greater breadth and depth of analysis, and to bridge physical, social, economic, and technological dimensions of the WEF nexus.

3.3.2. Methods that address the influence of context

The highly site-specific nature of the nexus linkages stresses the need for methods that consider local context. As Foran (2015) points out, context is critical for understanding social dynamics. While nexus research is rapidly expanding, understanding of the nexus' socio-political context has not been advancing similarly (Foran 2015). This includes recognizing the importance of the historical, institutional, and political context of water, energy, and food interactions and how they shape nexus outcomes in terms of political economy. Furthermore, with nexus interactions occurring across scales (in both time and space), nexus methods should consider the multi-scalar relationships of water, energy, and food systems (Hoff 2011, Bazilian *et al* 2011, Daher and Mohtar 2015, Smajgl *et al* 2016, Scott *et al* 2011). Finally, flexibility is an important attribute of nexus assessments, particularly to tailor methods to various geographic regions (Miralles-Wilhelm 2016) and spatial and temporal dynamics (Chang *et al* 2016), to allow for transferable principles across scales (Guillaume *et al* 2015), and to incorporate new knowledge (Zimmerman *et al* 2016). Considering how the resource nexus affects, and is affected by, socio-political systems also contributes toward achieving more inclusive and sustainable futures (UN 2015).

3.3.3. Collaborative approaches

Collaborative and participatory approaches serve nexus aims in two main ways: (1) they contribute new sources of knowledge to inform nexus conceptual models and quantitative model parameterization, and (2) they help align nexus assessments with stakeholders' needs. While many studies call for nexus methods to be more holistic (e.g. de Strasser *et al* 2016, Foran 2015) and include broad representation of actors (e.g. Mohtar and Lawford 2016), we argue that methods should enable cross-sectoral coordination and collaboration to address the broad scope of the nexus. Participatory processes, convergence thinking, and transdisciplinary approaches can effectively bring more voices and new perspectives into the discussion, support knowledge sharing, and effectively inform decision-making (Wolfe *et al* 2016, Howarth and Monasterolo 2016). Diverse perspectives help identify and characterize critical nexus attributes, but also shed light on stakeholders' values. As the lack of adequate data is a common limitation for studies using robust nexus methods (Ringler *et al* 2013, Wolfe *et al* 2016), data sharing platforms are needed to enable collaborative approaches (Wolfe *et al* 2016, Gallagher *et al* 2016) and should be transparent (Ringler *et al* 2013).

3.3.4. Methods that address policy needs or are feasible to implement in practice

Implementing the nexus to achieve desired results requires nexus assessments to be both operational in practice and closely attuned to policy and planning needs. There is a need for nexus analytical methods—articles that present directions for systematically assessing water, energy, food systems with corresponding case studies—to operationalize the nexus. Producing results that (1) address relevant policy questions, and (2) are accessible and usable by policy-makers and community decision-makers is challenging due to the inherent complexity of nexus questions, the interdisciplinary nature of nexus approaches, and the disconnect between research and policy arenas. However, transdisciplinary and participatory approaches, policy and institutional analyses, and scenario development can all help link nexus research with decision-making to influence policy and management. This integration requires science-policy dialogues to identify shared objectives, match spatial and temporal scales, and develop institutional mechanisms to facilitate policy coordination as described in Rasul's (2016) proposed policy framework for managing the WEF nexus. Additionally, as Gallagher *et al* (2016) suggest, researchers need to work with stakeholders to see what is politically acceptable, feasible, and where there is space to make improvements in policies (p. 14).

4. Select examples of nexus methods

We used the key features of nexus analytical approaches, summarized in figure 6, to categorize and analyze our sample set of 73 articles. We compared each article's methods to the key features: degree of innovation, influence of context, degree of collaboration, and ability to address policy needs or implement methods in practice, to see how current nexus analytical tools address the stated needs for nexus assessments described in the literature. Broad conceptual frameworks, such as the WEF nexus, allow for a plurality of approaches and their wide-reaching aims make it difficult for any single tool to be wholly sufficient. From the 73 articles analyzed, we highlight 18 articles that address multiple key features and represent the variety of methods used to apply the nexus concept. These articles are summarized in table 3. Although we focus on these 18 articles in table 3, in this section we also highlight other articles from our sample set ($n = 73$) that make important contributions in terms of innovation, context, collaboration, or implementation.

In table 3 we summarize each approach, stating the methods used, availability of tools, data requirements, co-benefits, and stated limitations of each method. We offer table 3 as a resource to help researchers and practitioners select and employ analytical approaches for nexus research, based on these examples of how different combinations of tools can be applied in different nexus contexts. We hope that these articles and their associated methods will not only contribute to a knowledge base of current approaches aligned with nexus thinking, but also promote continued development and evolution of robust nexus methods by demonstrating various ways in which nexus assessments can address innovation, context, collaboration, and implementation.

4.1. Examples of innovative methods

There are a host of studies that offer innovative methods to help quantify linkages and interactions among sectors, conceptualize dynamic feedbacks, and support mixed-method approaches to better understand WEF systems. Analytical methods used to represent nexus interactions are being improved by using robust analytical approaches (e.g. Howells *et al* 2013, Villarroel Walker *et al* 2012, 2014), new data (e.g. Semertzidis 2015 for use of remotely sensed data), as well as interactive data sharing platforms (e.g. Wolfe *et al* 2016 on 'cyber-platforms'). Perspectives such as systems-thinking, are used in new ways to shed light on sectoral feedback and system change using iterative (e.g. Halbe *et al* 2015) or dynamic approaches (e.g. Smajgl *et al* 2016).

We also see models being combined in novel ways to integrate physical, technical, social, and economic components of the nexus (e.g. Bazilian *et al* 2011, de Strasser *et al* 2016, Howells *et al* 2013, Ringler *et al* 2016, Semertzidis 2015, Welsch *et al* 2014, Yang *et al* 2016a, 2016b). Many integrated models utilize a module-based design that supports integration of sectoral models, while also creating a tool that is flexible and able to accommodate new inputs or module extensions. Decision-support tools are being created by combining physical models with scenario analysis. Scenario analyses allow decision-makers to compare the impact of different policies or actions on the physical/economic system being modeled. Scenarios may be based on participatory or user input, climate change projections, or proposed resource management policies. Additional features such as sensitivity or uncertainty analyses (e.g. Villarroel Walker *et al* 2012) can also make these approaches more robust.

Lastly, using mixed-method approaches, researchers combine qualitative and quantitative methods to attain a more holistic understanding of WEF systems than could have been achieved individually (e.g. Stucki and Sojamo 2012, Karlberg *et al* 2015, Smajgl *et al* 2016, Guillaume *et al* 2015, Endo *et al* 2015, de Strasser *et al* 2016). Endo *et al* (2015) compile and evaluate qualitative and quantitative methods from interdisciplinary and transdisciplinary approaches that can be combined sequentially to assess the WEF nexus. Endo *et al* (2015) suggest that qualitative methods, such as questionnaire surveys, ontology engineering, and integrated maps, can be used to describe the WEF nexus in different study contexts, design relevant analytical models, and guide research to address policy needs. Using a combination of mixed-methods, or selecting the most applicable approach for the site context, can provide a broader and deeper understanding of nexus interactions than studies that employ only one method (Endo *et al* 2015). This sequential approach provides the opportunity for participatory research design, iterative nexus analysis, and evaluation of policy options.

4.2. Methods that address the influence of context

Nexus drivers and interactions are often case-specific—a result of the local geography, climate, economy, history, resource demand, and other contextual factors. Although social science methods were used in only 19 studies (26% of the total, see table 1), these papers offer important insights into the contributions that social science methods make toward designing integrated policies and achieving equitable nexus tradeoffs by elucidating critical social, political, and historical dimensions of resource security.

Researchers address the local context by adjusting methods to the appropriate scale and boundaries of analysis, designing studies to be case-specific or assessing socio-political factors with qualitative analyses. We highlight a few examples here. Guillaume *et al* (2015) examine how to delineate appropriate boundaries for nexus assessments, how different system boundaries affect outcomes, and how inclusion/exclusion of different subsystems can alter nexus interactions, concluding that nexus boundaries

Table 3. Summary of select examples of nexus tools and methods.

Citation	Scale	Method	Methods used	Tool/method availability	Co-benefits	Stated limitations	Data requirements
Villarroel Walker *et al* 2014	City	Quantitative	• Multi-Sectoral Systems Analysis (combines Substance Flow Analysis, metabolic performance metrics, and Regionalized Sensitivity Analysis) • Scenario analysis	Analysis framework developed in Matlab. Not publicly-available.	• Integrated systems approach • Estimates economic benefits • Facilitates decision-support	• None stated	Data obtained from publicly-available databases from national governments and international organizations.
Wolfe *et al* 2016	Local, regional	Quantitative and qualitative	• Systems informatics • Information analysis • Systems analytics • Decision support systems • Scenario analysis • Transdisciplinary design	Cyber-physical framework for systems informatics, information analysis methods and tools, systems analytics and decision support (proposed).	• Facilitates sharing and integration of interdisciplinary datasets • Support for problem solving and decision-making • Framework for engaging stakeholders and developing communities-of-practice	• Limited data available at different scales (p. 176) and across a variety of systems (p. 173)	Generally, need better data coverage at various scales &improved data sharing among researchers and organizations.
Villamayor-Tomas *et al* 2015	Local, national	Qualitative	• Institutional Analysis and Development (IAD) Framework • Value chain analysis (as 'Networks of Action Situations' (NAS))	Approach described and referenced within Villamayor-Tomas *et al* 2015.	• Value-chain analysis identifies input-output and causal relationships • NAS accounts for actors' decisions • IAD assesses role of institutions	• Focus on provisioning services • Limited evaluation of institutional levels in various collective choice and operational situations • Lacks attention to political and negotiating power among actors (p. 750)	Combination of primary (i.e. semi-structured interviews, focus groups and surveys) and secondary data (i.e. academic literature).
Foran 2015	Regional	Qualitative	• Delphi process • Historical analysis • Critical discourse analysis	References for methods used are provided within Foran 2015.	• Offers social structure and political context to the WEF nexus	• Limited analysis of system dynamics	Not specified.

Table 3. *Continued.*

Citation	Scale	Method	Methods used	Tool/method availability	Co-benefits	Stated limitations	Data requirements
Hurford and Harou 2014	Regional	Quantitative	• Multi-criteria search (optimization) algorithm • Tradeoff simulator • Visual analytics • Water management modeling	IRAS-2010 (open-source), -NSGAII algorithm.	• Investigates how new investments impact tradeoffs • Visualization assists communication and decision-making • Can analyze large solution sets	• Does not include capital and operational costs or non-water-related benefits • Does not consider uncertainty of future flows • Requires information on ecosystem services and resource use for objective functions	Resource demand data. Flow and abstraction. Revenue and deficit data. Flow alteration. Stakeholders to define metrics and objectives.
Endo *et al* 2015	Regional	Quantitative and qualitative	• Questionnaire surveys • Physical models • Benefit-Cost Analysis • Integrated Indices • Optimization Management Tools • Ontology Engineering • Integrated Maps	Varies, discussed within Endo *et al* 2015.	• Synthesizes across spatial and temporal scales • Qualitative methods facilitate inter- and transdisciplinary collaboration and feasibility of cross-sector policies • Quantitative methods estimate impacts of endogenous and exogenous factors, compare costs and benefits, provide thresholds to inform decisions, and optimize allocations	• Integrating various spatial and temporal scales • Different methods appropriate for different cases, contexts and stages of assessment (p. 5822)	Questionnaires, ontology engineering and integrated maps require data obtained through participatory processes. Benefit-costs analysis, indices, and physical models require primary data and measurements. Interdisciplinary teams needed.
Karlberg *et al* 2015	Regional	Quantitative and qualitative	• Interdisciplinary modeling • Stakeholder mapping • Interviews • Participatory scenario planning and analysis • Strengths, weaknesses, opportunities, threats (SWOT) analysis	WEAP, LEAP, participatory approach with stakeholders and scientists.	• Robust water resources/ biomass, and energy/climate modeling modules • 'Story And Simulation' approach translates qualitative scenarios into quantitative assessment • SWOT analysis facilitates decision-making • Iterative process helps gain stakeholders support for resultant solutions/policy	• Limited in scope • Does not include qualitative aspects of water, spatio-temporal aspects of hydrologic regime, and ecological processes	WEAP, LEAP, and participants.

Table 3. *Continued.*

Citation	Scale	Method	Methods used	Tool/method availability	Co-benefits	Stated limitations	Data requirements
Stucki and Sojamo 2012	Regional, national	Quantitative and qualitative	• Quantitative indicators • Critical discourse analysis	Approach for this study was described within Stucki and Sojamo 2012.	• Quantitative indicators reduce complexity and allow for comparison • Critical discourse analysis examines global political economy context to identify external drivers	• Linkages between indicators complex without computerized approaches • Data combinations and degrees of certainty vary • Need to address uncertainty (p. 415)	Indicator data were collected from publicly available sources, mostly grey literature. Discourse analysis was conducted on academic and grey literature.
Daher and Mohtar 2015	National	Quantitative	• Input/output • Systems modeling • Focus groups • Scenario planning	WEF Nexus Tool 2.0. Free, available online.	• Offers platform to evaluate scenarios and identify resource allocation strategies • Quantitative and input/output approaches facilitate scenario comparison	• Designed for Qatar • Limited to national scale	National level percentages of water and energy use, sources, agricultural production, food importation.
Halbe *et al* 2015	National	Qualitative	• Stakeholder analysis • Participatory Model Building • Causal Loop Diagrams (CLD) • Learning assessment	Methodology described and referenced within Halbe *et al* 2015.	• CLDs are used to collect and compare stakeholder perspectives • Learning assessment fosters knowledge and skill development that facilitates implementation • Participatory model building engages stakeholders to identify strategies and barriers	• Limited to qualitative analysis • Requires substantial simplifications • Difficult to resolve conflictual or redundant information • Challenging to utilize CLD data due to a high number of variables and causal linkages (p. 890)	Stakeholder participation.
Howarth and Monasterolo 2016	National	Qualitative	• Participatory workshops	Participatory workshops described within Howarth and Monasterolo 2016.	• Identifies stakeholders' concerns to inform nexus decision-making, collaboration and communication • Engages a diverse group of stakeholders in knowledge production	• Limited sample size and geographic representation of participants (p. 56)	Stakeholder participation.

Table 3. *Continued.*

Citation	Scale	Method	Methods used	Tool/method availability	Co-benefits	Stated limitations	Data requirements
Howells *et al* 2013	National	Quantitative	• CLEWs (Climate, Land-use, Energy and Water) integrated model (modules include WEAP, LEAP and AEZ sector-based quantitative models) • Scenario analysis	Further development by the International Atomic Energy Agency, modules developed by Stockholm Environment Institute, the International Institute for Applied Systems Analysis and FAO.	• Robust quantitative modeling integrates multiple sectors and their interactions using an iterative, module-based approach • Integrates climate scenarios • Investigates interdependencies of and trade-offs among resource systems to inform coherent policy-making • Builds on existing modeling methodologies	• Time-intensive and data-intensive • High model uncertainty	Detailed biophysical datasets and climate scenario data.
de Strasser *et al* 2016	Transboundary	Quantitative and qualitative	• Questionnaires • Workshops/meeting • Demographic data analysis • Nexus dialogues • Resource flows • Document analysis • Governance analysis • Indicators	Transboundary River Basin Nexus Approach (TRBNA). Six-step methodology available from UNECE.	• Proposes policy and technical actions across scales • Involves key economic sectors in decision-making in transboundary contexts • Encourages cross-sectoral dialogue and transboundary cooperation • Identifies stakeholder priorities to develop operational solutions	• Ambiguous definitions • Inconsistent indicators • Does not address financial social, and power issues • Water-centric	National and international statistics, river basin management plans, interviews and questionnaires with experts, existing databases and reports, stakeholder participants.
Guillaume *et al* 2015	Transboundary	Quantitative and qualitative	• WaterGAP global water model • Spatiotemporal assessment • Historical analysis	WaterGap Model developed by Universities of Kassel and Frankfurt. Not publicly available.	• Offers five transferable principles to relate case study to global trends • Considers role of subsystems outside of WEF nexus, e.g. water resources • Engages global-scale data (to increase comparability) along with local data • Engages with global drivers (development, globalization) • Considers the effect of system boundaries and externalities	• Utilizes modeled data versus measurements • Many assumptions in model (p. 4212, 4223) • Water-centric	Publicly-available, monthly water availability and consumption data. Publicly-available socio-economic data. Regional datasets integrated when available.

Table 3. *Continued.*

Citation	Scale	Method	Methods used	Tool/method availability	Co-benefits	Stated limitations	Data requirements
Smajgl *et al* 2016	Transboundary	Quantitative and qualitative	• Delphi technique • Participatory processes • Agent based modelling • Scenario analysis • Qualitative relationship and stochastic approaches • Static comparative analysis • Cause-effect chains • System diagrams	Mixed-method participatory approach, monitoring and evaluation and agent based modeling described within Smajgl *et al* 2016.	• Identifies advantages of sectorally-balanced, dynamic nexus approach • Minimizes sector-related biases • Robust characterization of nexus interactions • Engages experts and stakeholders to address policy-needs	• Bias and preconceptions about causal relationships possible	Experiences of local experts.
Soliev *et al* 2015	Transboundary	Quantitative and qualitative	• Historical analysis • Institutional analysis	Historical analysis described within. Utilizes Williamson's framework[5] of institutional analysis (p. 2734).	• Facilitates understanding in complex institutional and resource environments • Benefit-sharing approach facilitates transboundary cooperation • Historical and institutional approach informs policy by reconciling global objectives with local economic goals • Highlights indirect costs associated with benefits	• None stated	The data were gathered through archival research (e.g. laws, decrees, agreements, declarations, etc.).

[5] See Williamson 1998.

Table 3. *Continued.*

Citation	Scale	Method	Methods used	Tool/method availability	Co-benefits	Stated limitations	Data requirements
Yang *et al* 2016b	Transboundary	Quantitative	• Hydrologic modeling • Hydro-economic modeling • Ex-post scenario analysis • Decision-scaling framework	BRAHEMO (BRAhmaptura HydroEconomic Model). Climate and land use change scenarios. Methodology applicable worldwide, if sufficient data are available.	• Assess different drivers of the WEF nexus • Evaluates development and climate change scenarios • Identifies impact of climate and competing water needs • Coupled approach supports policy-relevant solutions	• Not comprehensive • Simplistic thresholds • Social drivers difficult to estimate • Population growth not modeled • Simplifying assumptions and inherent uncertainty. • Limited applicability due to data requirements (p. 27)	Agricultural, hydropower, domestic water use, groundwater pumping and streamflow data are needed. Climate scenarios and potential water diversions.
Ringler *et al* 2016	Global	Quantitative	• Global computable general equilibrium model (GLOBE) • IMPACT3 (modular integrated assessment model) • Scenario analysis	Approach is described within. Links GLOBE model with IFPRI's IMPACT v3[6] (p. 162).	• Facilities a detailed analysis of the effects of WEF shocks • Assesses impact of changes in global fossil fuel prices • Examines climate scenarios • Examines role of pricing and other economic tools for addressing nexus tradeoffs • Assess impacts of direct and indirect shocks to food sector	• Relies on economic models • Mostly quantitative data sources • Limited drivers of change considered	Details about input data and scenarios are included in Appendices within. GTAP 8.1 database utilized to calibrate the GLOBE model. Model was run with the HADGEM2-ES.

[6] See Robinson *et al* 2015.

need to be defined on a case-by-case basis. For example, they examine nexus interactions within politically relevant spatial units defined by a combination of river basin boundaries and economic regions (Guillaume *et al* 2015). To better address the underlying power relations of the resource nexus, Foran (2015) analyzes discourses, institutions, and individual interests to understand how uneven development practices are deeply embedded in social structures and political contexts. A historical and institutional analysis by Soliev *et al* (2015) helped to identify multiple factors (i.e. economic, social, and political) that hinder or enable integration across sectors. Similarly, Villamayor-Tomas *et al* (2015) use an institutional analysis to explore the role of institutions and actors in facilitating or limiting nexus integration. Understanding this complexity is a first step to develop appropriate policy and management strategies for WEF systems (Soliev *et al* 2015). Other papers highlighted in table 3 emphasize a case-specific approach to incorporate influential aspects of the local context (e.g. Halbe *et al* 2015, de Strasser *et al* 2016).

4.3. Examples of collaborative approaches

Many of our highlighted studies demonstrate the role of stakeholders in advancing nexus assessments. Transdisciplinary methods aim for broad participation and to incorporate knowledge from various sources, such as academic research, on-the-ground practitioner experience, and local knowledge (Mauser *et al* 2013). By participating in the research process, stakeholders help guide the research questions, and study design. Transdisciplinary approaches are used to identify inter-sectoral relationships, achieve more holistic assessments, and improve integration of policy among sectors (Endo *et al* 2015).

Such approaches can offer insight into the social dynamics of the nexus. Howarth and Monasterolo (2016) use a transdisciplinary approach and participatory processes to work with decision-makers to identify barriers to integration across sectors and improve resource policy. To capture a range of perceptions, Halbe *et al* (2015) engage stakeholders in individual, group, organizational, and government level decision-making to co-develop resource governance. By implementing an iterative approach, stakeholders' conceptual diagrams of water, energy and food resource system interactions inform the design of quantitative nexus models which are subsequently used to promote utilization of sustainable WEF strategies (e.g. grey water recycling or aquaponics) through improved community or organizational education (Halbe *et al* 2015).

4.4. Methods that address policy needs or are feasible to implement in practice

Most nexus studies aim to improve coordination and integration of sector-based resource policies. Strategies to better address policy needs include scenario analysis, site-specific research designs, and engaging stakeholders and policy-makers in participatory activities. Many of these strategies also are used to address other key features of nexus methods, as discussed above.

As discussed in section 4.1, quantitative studies commonly incorporate scenario analyses to make results of integrated modeling assessments useful in decision-making. If computational models provide the ability to test realistic options (Endo *et al* 2015), this combined approach can be useful for linking nexus assessments with decision-making (e.g. Ringler *et al* 2016, Topi *et al* 2016, van Vuuren *et al* 2015). Other nexus studies focus on improving data availability, data systems, and analytics to produce 'actionable decision support' for multiple users, including decision-makers, practitioners, and researchers (Wolfe *et al* 2016: 174). Advanced visualization of cross-sectoral trade-offs also helps decision-makers develop and explore alternative resource management plans (Hurford and Harou 2014). Howarth and Monasterolo (2016) rely on transdisciplinary and participatory processes that actively engage stakeholders in producing nexus knowledge that reflects stakeholder concerns and perspectives. Through an iterative process of multiple participatory workshops with diverse stakeholder groups, topics of interest and important themes were identified by stakeholders themselves.

To make nexus assessments feasible for on-the-ground implementation, authors use a variety of approaches that either make assessment methods more generalizable or, conversely, provide detailed methods to address site-specific questions. Guillaume *et al* (2015) approach derives transferrable principles of WEF nexus management from multiple case studies. In contrast, de Strasser *et al* (2016) present a step-by-step participatory nexus assessment methodology, designed to draw out details to clarify site-specific nexus interactions.

5. Conclusions

In this paper, we have addressed the need for a knowledge base of WEF nexus methods that exemplify the nexus conceptual approach for addressing the inherent complexity of water, energy, and food resource interactions. We reviewed the current state of research on nexus analytical approaches and provided (1) a catalog of nexus tools and methods (see table 1); (2) 18 articles demonstrating promising methods (see table 3); and, (3) four key features of WEF analytical approaches derived from the body of WEF literature (see figure 6). By providing these resources for researchers and practitioners looking to conduct nexus assessments, this paper promotes the coordinated development of nexus-specific tools and methods that align with nexus thinking.

Our review and analysis reveal that nexus methods are not clearly correlated with nexus conceptualizations, a disjuncture that may limit progress toward improved WEF resource management, harmonized cross-sectoral resource policies, and sustainable outcomes across water, energy, and food systems. We found that integrated models, economic tools, and environmental management approaches have dominated the landscape of nexus methods, and, while these established techniques offer many useful approaches, new perspectives that expand our understanding of WEF interactions and independencies are needed. Such methods designed specifically for nexus analysis also need to address the social and political context of water, energy, and food systems to achieve optimal solutions.

The nexus concept can be better operationalized as an analytical tool by utilizing approaches that address the four key features identified in this review—innovation, social and political context, collaboration, and implementation in policy and practice. Promising approaches we identified include using interdisciplinary and mixed-methods, and incorporating transdisciplinary or participatory approaches. Further, analyses should target policy- and community-relevant scales. Interdisciplinary and mixed-method approaches that combine quantitative and qualitative methods from multiple disciplines are needed to address the physical and social aspects of water, energy, and food systems. The contribution of social science approaches here is significant, particularly for understanding the social and political context of WEF interactions and feedbacks for resources efficiency, policy integration, and sustainable development. While data from multiple sectors are often utilized, transdisciplinary and participatory approaches that work with stakeholders, decision-makers, and policy-makers in water, energy, and food fields can help align nexus research with policy needs and support its utilization in practice. Further, nexus methods and tools must be made available for use by practitioners and researchers alike.

Given the plurality of drivers and dimensions of the WEF nexus, we support the use of multiple approaches to help find innovative ways to study WEF nexus interactions, address local context, promote collaboration, and address policy needs and support implementation in practice. Developing approaches that provide useful and relevant information to guide inter-sectoral policy coordination is crucial. While many studies offer decision-support, nexus assessments can better link with policy outcomes by drawing from diverse knowledge bases and deeply engaging both stakeholders and decision-makers. Overall, while the WEF nexus offers a promising approach to addressing complex resources and development challenges, it begs more nuanced methodological development to be more effective as a policy-relevant approach.

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6. Appendix: Articles included in the subset for systematic review ($n = 73$)

	Year	Authors	Title	Journal
1	2015	Al-Ansari T, Korre A, Nie Z, Shah N	Development of a life cycle assessment tool for the assessment of food production systems within the energy, water and food nexus.	*Sustainable Production and Consumption*
2	2016	Bekchanov, M, Lamers, J P A	The effect of energy constraints on water allocation decisions: The elaboration and application of a system-wide economic-water-energy model (SEWEM).	*Water*
3	2016	Bonsch, M *et al*	Trade-offs between land and water requirements for large-scale bioenergy production.	*GCB Bioenergy*
4	2015	Bowe, C, van der Horst, D V	Positive externalities, knowledge exchange and corporate farm extension services; a case study on creating shared value in a water scarce area.	*Ecosystem Services*
5	2016	Cottee J *et al*	The local nexus network: Exploring the future of localised food systems and associated energy and water supply.	*Smart Innovation, Systems and Technologies*
6	2014	Daccache A, Ciurana J S, Rodriguez Diaz, J A, Knox, J W	Water and energy footprint of irrigated agriculture in the Mediterranean region.	*Environmental Research Letters*
7	2015	Daher, B T, Mohtar, R H	Water–energy–food (WEF) Nexus Tool 2.0: guiding integrative resource planning and decision-making.	*Water International*
8	2016	Damerau K, Patt A G, van Vliet O P R	Water saving potentials and possible trade-offs for future food and energy supply.	*Global Environmental Change*
9	2016	De Laurentiis, V, Hunt, D V L, Rogers, C D F	Overcoming food security challenges within an energy/water/food nexus (EWFN) approach.	*Sustainability*
10	2016	de Strasser, L, Lipponen, A, Howells, M, Stec, S, Bréthaut, C	A methodology to assess the water energy food ecosystems nexus in transboundary river basins.	*Water*
11	2015	Doukkali M R, Lejars C	Energy cost of irrigation policy in Morocco: a social accounting matrix assessment.	*International Journal of Water Resources Development*
12	2016	Elbehri, A, Sadiddin, A	Climate change adaptation solutions for the green sectors of selected zones in the MENA region.	*Journal of Food, Agriculture and Society*
13	2015	Endo, A, Burnett, K, Orencio, P M, Kumazawa, T, Wada, C A, Ishii, A, Tsurita, I, Taniguchi, M	Methods of the water-energy-food nexus.	*Water*
14	2015	Foran, T	Node and regime: Interdisciplinary analysis of water-energy-food nexus in the Mekong region.	*Water Alternatives*
15	2016	Giupponi, C, Gain, A K	Integrated spatial assessment of the water, energy and food dimensions of the Sustainable Development Goals.	*Regional Environmental Change*
16	2015	Guillaume, J H A, Kummu, M, Eisner, S, Varis, O	Transferable principles for managing the nexus: Lessons from historical global water modelling of central Asia.	*Water*
17	2015	Haie, N	Sefficiency (sustainable efficiency) of water–energy–food entangled systems.	*International Journal of Water Resources Development*
18	2015	Halbe, J, Pahl-Wostl, C, A Lange, M, Velonis, C	Governance of transitions towards sustainable development—the water–energy–food nexus in Cyprus.	*Water International*
19	2015	Heckl, I, Cabezas, H, Friedler, F	Designing sustainable supply chains in the energy-water-food nexus by the P-graph methodology.	*Chemical Engineering Transactions*
20	2016	Howarth, C, Monasterolo, I	Understanding barriers to decision making in the UK energy-food-water nexus: The added value of interdisciplinary approaches.	*Environmental Science and Policy*
21	2013	Howells *et al*	Integrated analysis of climate change, land-use, energy and water strategies.	*Nature Climate Change*
22	2014	Hurford A P, Harou J J	Balancing ecosystem services with energy and food security – Assessing trade-offs from reservoir operation and irrigation investments in Kenya's Tana Basin.	*Hydrology and Earth System Sciences*
23	2015	Irabien A, Darton R C	Energy–water–food nexus in the Spanish greenhouse tomato production.	*Clean Technologies and Environmental Policy*
24	2015	Jalilov S, Varis O, Keskinen M	Sharing benefits in transboundary rivers: An experimental case study of Central Asian water-energy-agriculture nexus.	*Water*

	Year	Authors	Title	Journal
25	2016	Jalilov S M, Keskinen M, Varis O, Amer S, Ward F A	Managing the water-energy-food nexus: Gains and losses from new water development in Amu Darya River Basin.	*Journal of Hydrology*
26	2015	Kajenthira Grindle A, Siddiqi A, Anadon L D	Food security amidst water scarcity: Insights on sustainable food production from Saudi Arabia.	*Sustainable Production and Consumption*
27	2016	Karabulut A *et al*	Mapping water provisioning services to support the ecosystem-water-food-energy nexus in the Danube river basin.	*Ecosystem Services*
28	2015	Karlberg L *et al*	Tackling complexity: Understanding the food-energy-environment nexus in Ethiopia's lake TANA sub-basin.	*Water Alternatives*
29	2015	Keskinen M, Someth P, Salmivaara A, Kummu M	Water-energy-food nexus in a transboundary river basin: The case of Tonle Sap Lake Mekong River Basin.	*Water*
30	2016	King C W, Carbajales-Dale M	Food-energy-water metrics across scales: project to system level.	*Journal of Environmental Studies and Sciences*
31	2015	King C, Jaafar H	Rapid assessment of the water–energy–food–climate nexus in six selected basins of North Africa and West Asia undergoing transitions and scarcity threats.	*International Journal of Water Resources Development*
32	2014	Lacirignola C, Capone R, Debs P, El Bilali H, Bottalico F	Natural resources—food nexus: food-related environmental footprints in the Mediterranean countries.	*Frontiers in Nutrition*
33	2016	Leung Pah Hang M Y, Martinez-Hernandez E, Leach M, Yang A	Designing integrated local production systems: A study on the food-energy-water nexus.	*Journal of Cleaner Production*
34	2013a	Li C, Wang Y, Qiu G	Water and energy consumption by agriculture in the Minqin Oasis Region.	*Journal of Integrative Agriculture*
35	2016	Li G, Huang D, Li Y	China's input-output efficiency of water-energy-food nexus based on the data envelopment analysis (DEA) model.	*Sustainability*
36	2013b	Li W Li L, Qiu G	General nexus between water and electricity use and its implication for urban agricultural sustainability: A case study of Shenzhen South China.	*Journal of Integrative Agriculture*
37	2014	Martin-Gorriz B, Soto-García, M, Martínez-Alvarez V	Energy and greenhouse-gas emissions in irrigated agriculture of SE.	*Energy*
38	2015	Mayor B, López-Gunn E, Villarroya F I, Montero E	Application of a water–energy–food nexus framework for the Duero river basin in Spain.	*Water International*
39	2016	Moioli E, Manenti F, Rulli M C	Assessment of global sustainability of bioenergy production in a water-food-energy perspective.	*Chemical Engineering Transactions*
40	2015a	Mukuve F M, Fenner R A	The influence of water land energy and soil-nutrient resource interactions on the food system in Uganda.	*Food Policy*
41	2015b	Mukuve F M, Fenner R A	Scale variability of water land and energy resource interactions and their influence on the food system in Uganda.	*Sustainable Production and Consumption*
42	2015	Olsson A, Campana P E, Lind M, Yan J	PV water pumping for carbon sequestration in dry land agriculture.	*Energy Conversion and Management*
43	2015	Ozturk I	Sustainability in the food-energy-water nexus: Evidence from BRICS (Brazil the Russian Federation India China and South Africa) countries.	*Energy*
44	2015	Pacetti T, Lombardi L, Federici G	Water-energy Nexus: A case of biogas production from energy crops evaluated by Water Footprint and Life Cycle Assessment (LCA) methods.	*Journal of Cleaner Production*
45	2016	Perrone D, Hornberger G	Frontiers of the food-energy-water trilemma: Sri Lanka as a microcosm of tradeoffs.	*Environmental Research Letters*
46	2016	Pittock J, Dumaresq D, Bassi A M	Modeling the hydropower-food nexus in large river basins: A Mekong case study.	*Water*
47	2015	Pradeleix L, Roux P, Bouarfa S, Jaouani B, Lili-Chabaane Z, Bellon-Maurel V	Environmental impacts of contrasted groundwater pumping systems assessed by life cycle assessment methodology: Contribution to the water-energy nexus study.	*Irrigation and Drainage*
48	2016	Ravi S, Macknick J, Lobell D, Field C, Ganesan K, Jain R, Elchinger M, Stoltenberg B	Colocation opportunities for large solar infrastructures and agriculture in drylands.	*Applied Energy*
49	2016	Ringler C, Willenbockel D, Perez N, Rosegrant M, Zhu T, Matthews N	Global linkages among energy food and water: an economic assessment.	*Journal of Environmental Studies and Sciences*
50	2015	Roibás, L, Elbehri A, Hospido A	Evaluating the sustainability of Ecuadorian bananas: Carbon footprint water usage and wealth distribution along the supply chain.	*Sustainable Production and Consumption*

	Year	Authors	Title	Journal
51	2016	Rulli M C, Bellomi D, Cazzoli A, De Carolis G, D'Odorico P	The water-land-food nexus of first-generation biofuels.	*Scientific Reports*
52	2016	Sanders K T, Masri S F	The energy-water agriculture nexus: The past present and future of holistic resource management via remote sensing technologies.	*Journal of Cleaner Production*
53	2011	Scott C A	The water-energy-climate nexus: Resources and policy outlook for aquifers in Mexico.	*Water Resources Research*
54	2015	Scott C A, Sugg Z P	Global energy development and climate-induced water scarcity-Physical limits sectoral constraints and policy imperatives.	*Energies*
55	2010	Sharma B *et al*	The Indus and the Ganges: River basins under extreme pressure.	*Water International*
56	2016	Smajgl A, Ward J, Pluschke L	The water-food-energy Nexus—Realising a new paradigm.	*Journal of Hydrology*
57	2016	Smidt S J, Haacker E M K, Kendall A D, Deines J M, Pei L, Cotterman K A, Li H, Liu X, Basso B, Hyndman D W	Complex water management in modern agriculture: Trends in the water-energy-food nexus over the High Plains Aquifer.	*Science of the Total Environment*
58	2015	Soliev I, Wegerich K, Kazbekov J	The costs of benefit sharing: Historical and institutional analysis of shared water development in the Ferghana Valley the Syr Darya Basin.	*Water*
59	2012	Stucki V, Sojamo S	Nouns and Numbers of the Water-Energy-Security Nexus in Central Asia.	*International Journal of Water Resources Development*
60	2015	Talozi S, Al Sakaji Y, Altz-Stamm A	Towards a water–energy–food nexus policy: realizing the blue and green virtual water of agriculture in Jordan.	*International Journal of Water Resources Development*
61	2016	Topi C, Esposto E, Marini Govigli V	The economics of green transition strategies for cities: Can low carbon energy efficient development approaches be adapted to demand side urban water efficiency?	*Environmental Science and Policy*
62	2015	van Vuuren D P *et al*	Pathways to achieve a set of ambitious global sustainability objectives by 2050: Explorations using the IMAGE integrated assessment model.	*Technological Forecasting and Social Change*
63	2015	Villamayor-Tomas S, Grundmann P, Epstein G, Evans T, Kimmich C	The water-energy-food security nexus through the lenses of the value chain and the institutional analysis and development frameworks.	*Water Alternatives*
64	2012	Villarroel Walker R, Beck M B, Hall J W	Water—and nutrient and energy—systems in urbanizing watersheds.	*Frontiers of Environmental Science and Engineering in China*
65	2014	Villarroel Walker R, Beck M B, Hall J W, Dawson R J, Heidrich O	The energy-water-food nexus: Strategic analysis of technologies for transforming the urban metabolism.	*Journal of Environmental Management*
66	2014	Vlotman W F, Ballard C	Water food and energy supply chains for a green economy.	*Irrigation and Drainage*
67	2016	Walsh M J, Gerber Van Doren L, Sills D L, Archibald I, Beal C M, Lei X G, Huntley M E, Johnson Z, Greene C H	Algal food and fuel coproduction can mitigate greenhouse gas emissions while improving land and water-use efficiency.	*Environmental Research Letters*
68	2014	Welsch M, *et al*	Adding value with CLEWS—modelling the energy system and its interdependencies for Mauritius.	*Applied Energy*
69	2016	Wolfe M L, Ting K C, Scott N, Sharpley A, Jones J W, Verma L	Engineering solutions for food-energy-water systems: it is more than engineering.	*Journal of Environmental Studies and Sciences*
70	2016	Xiang X, Svensson J, & Jia S	Will the energy industry drain the water used for agricultural irrigation in the yellow river basin?	*International Journal of Water Resources Development*
71	2016a	Yang Y C E, Ringler C, Brown C, Mondal M A H	Modeling the agricultural water-energy-food nexus in the Indus River Basin Pakistan.	*Journal of Water Resources Planning and Management*
72	2016b	Yang Y C E, Wi S, Ray P A, Brown C M, Khalil A F	The future nexus of the Brahmaputra River Basin: Climate water energy and food trajectories.	*Global Environmental Change*
73	2016	Zimmerman R, Zhu Q, Dimitri C	Promoting resilience for food energy and water interdependencies.	*Journal of Environmental Studies and Sciences*

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