Chapter 18
Developing a Framework for the Water-Energy-Food Nexus in South Africa

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Abstract The water-energy-food (WEF) nexus is a cross-sectoral approach to resource management and sustainable development. We propose a framework for linking the WEF nexus to the Sustainable Development Goals (SDGs), emphasizing SDG 2, 6 and 7. We further propose indices and models to evaluate WEF nexus performance. A systematic analysis of existing WEF nexus frameworks in academic and gray literature resulted in the development of a South African framework that considers the three sectors as well as technological innovation, human well-being, the SDGs, and different drivers of the WEF nexus. It is proposed that this framework be utilized as a point of departure for future research related to the WEF nexus in South Africa. Future research on the WEF nexus should focus on (i) developing an integrated model and indices to assess WEF resources in South Africa and creating a WEF nexus database; (ii) translating existing knowledge to inform policies for integrated sustainable resource management; and (iii) undertaking participatory research

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to demonstrate the applicability of the WEF nexus at the local level, focusing on the poor. The development of a WEF nexus model and indices is a pathway for unlocking the value of existing Resources data indices to integration generate sustainability new datasets.

Keywords Resources · Indices · Integration · Metrics · Models · Sustainability

1 Introduction

Sustainable resource management is a major worldwide governance concern as the demand for natural resources has increased exponentially with population and economic growth Sustainable resource management since the 1960s, when the Green Revolution was ushered in. Human resource consumption is disproportionate to the size of populations, with the wealthiest continents (North America and Europe) consuming on average ten times as much as poor continents (Africa , West Asia, etc.) (UNEP 2016), while the wealthy countries also contribute disproportionately to environmental pollution. International trade of natural resources contributes significantly to the Gross Domestic Product (GDP) of many developing countries, but is often perceived to be a "curse," because countries with an abundance of natural resources also tend to suffer from poverty, inequality, conflict, and insecurity (Ross 1999). An integrated approach to managing natural resources is required if the Sustainable Development Goals (SDGs) are to be realized by 2030.

Since 2011, the water-energy-food (WEF) nexus has been investigated from many points of view, each interest framing its analysis through the lens of its own economic, political, social, or scientific perspective. The WEF nexus is broadly defined as a framework that accounts for the interactions, synergies, and trade-offs among water, energy, and food when managing these resources. Water, energy, and food securities are inextricably linked, with usage within one sector influencing the use and availability of the others. Unlike Integrated Water Resource Management (IWRM), which is by definition water-centric, the WEF nexus approaches resource management holistically. Each resource sector within the nexus is considered equally important. The WEF nexus presents an opportunity for policymakers, researchers, and development agencies to optimize resources, maximize synergies and trade-offs, minimize ineffective redundancy of effort, and reduce conflicts among stakeholders representing each resource.

The WEF nexus is closely aligned with the SDGs, particularly SDG 2 (zero hunger), 6 (clean water and sanitation), and 7 (affordable and clean energy). Originally, the SDGs (the successor to the Millennium Development Goals (MDGs)) were established as a response to world poverty, inequality, and insecurity, but they have evolved into guiding principles for resource management. Developing countries, including South Africa , are likely to benefit greatly from the integrated resource management approach that the WEF nexus provides, particularly those countries experiencing significant trade-offs among water, energy, and food. The WEF nexus framework is particularly relevant when considering the recent proposed policy shift on land expropriation, which if adopted will significantly influence land utilization. Currently, various government agencies generally approach resource management in isolation, without accounting for the usage of water, energy, and land by other sectors. This is a major challenge in South African policymaking, especially considering the country's limited water availability, threats posed by both climate variability and change across climate-sensitive sectors, the scarcity of high-potential arable land, and the country's reliance on fossil fuel-based energy generation. Furthermore, climate change is expected to further compromise the availability of resources in South Africa, through changes to ecosystem services, rainfall frequency and distribution, and natural disasters.

South Africa is a water-scarce country with approximately 13% arable land, much of which is in regions that have a high concentration of mineral resources, e.g., coal. About 30% of South Africa's crops are grown on irrigated land, accounting for approximately 75% of total national agricultural water use (Ololade et al. 2017). From 1985 to 2008, South Africa was a net food exporter (Ololade et al. 2017). However, this has changed in recent years due to a reduction in agricultural yields and an increase in population (Ololade et al. 2017), on top of the country's heavy reliance on non-renewable energy resources (Ololade et al. 2017). Due to projected population growth and economic development, multiple countries within the Southern African Development Community (SADC) will be water-stressed by 2040, with South Africa experiencing a high ratio of water withdrawals to supply (World Resources Institute, 2015). It is therefore necessary to operationalize an inter-sectoral framework to understand dynamics among water, energy, and food systems for sustainable resource management and regional development.

This chapter seeks to develop a draft framework for implementing the WEF nexus for South Africa , linked to the Sustainable Development Goals (SDGs) and emphasizing SDGs 2, 6, and 7. We also propose indices and/or metrics as well as models that can be used to evaluate WEF nexus performance.

1.1 Current Status of the WEF Nexus in South Africa

Achieving water, energy, and food security is essential to South Africa's developmental agenda and aspirations to address existing inequalities and improving the quality of life for all. Approaches to WEF security must therefore be integrated with South Africa's primary focus on employment, poverty alleviation, equality, and the elimination of corruption. Responsibility for tackling these challenges is shared by the government at the national, provincial, and local levels. Progress toward achieving the SDGs consequently also depends on breaking down the "silo" mentality between government sectors. Despite the relative sophistication and success of South Africa in developing sound public policy, it is still too often compartmentalized by sector. This was the case in the adoption of the Millennium Development Goals (MDGs), which often lacked harmonization and thus failed to deliver as effectively as it otherwise could have.

In 2014, the Worldwide Fund/South Africa (WWF-SA) published a series of documents, funded by the British High Commission in Pretoria, entitled *Understanding the Food Energy Water Nexus* (Carter and Gulati 2014). The framework for approaching the WEF nexus was through the relationship of climate change, waste management, financial flows, and integrated planning to various disciplinary perspectives. South Africa For example, for energy, South Africa is taking advantage of its geographic location and ecosystem to develop renewable energy generation projects (see Fig. 1). The focus is on wind power generation and photovoltaic energy conversion, with relatively few concentrated solar power (CSP) and photovoltaic energy projects in the southern portion of the Northern Cape. Similarly, energy generated through biomass must be rainfed and not use irrigation (Nhamo et al. 2018).

Figure 2 shows changes in WEF nexus elements since 1999 in South Africa, revealing a definitive decrease in the food deficit over time, and an improving trend for sanitation facilities, as well as improved access to water and electricity. Simpson and Berchner (2017) indicate that South Africa currently fulfills its own demand for cereals. Less than 5% of the population is undernourished, and most of the population has access to clean and safe drinking water sources (in 2015, 93.2% of the population had access to improved water sources) and reliable electricity (in 2014, 86% of the population had access to electricity, albeit predominantly fossil fuel-based).

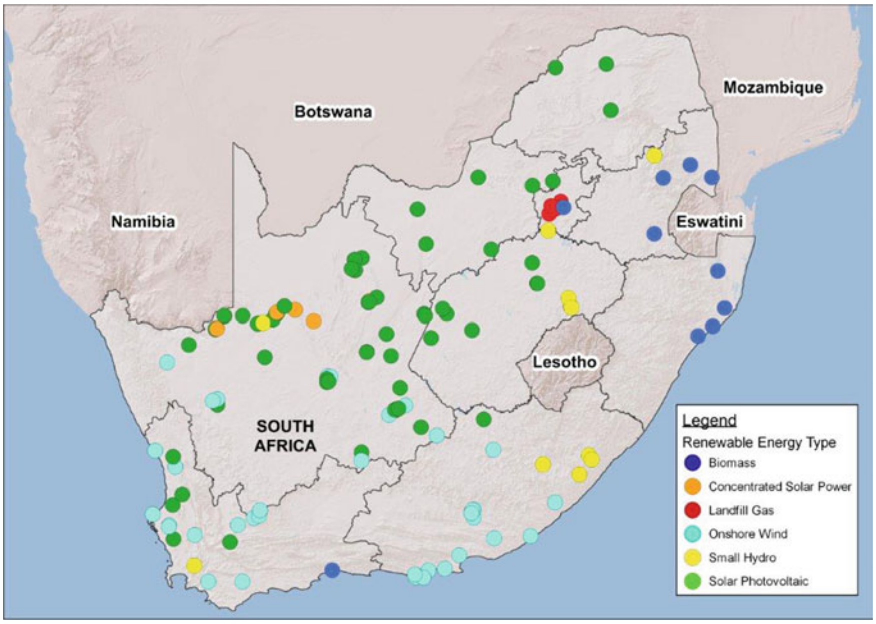

Fig. 1 Renewable energy projects in South Africa , as at 2018 (REDIS 2018)

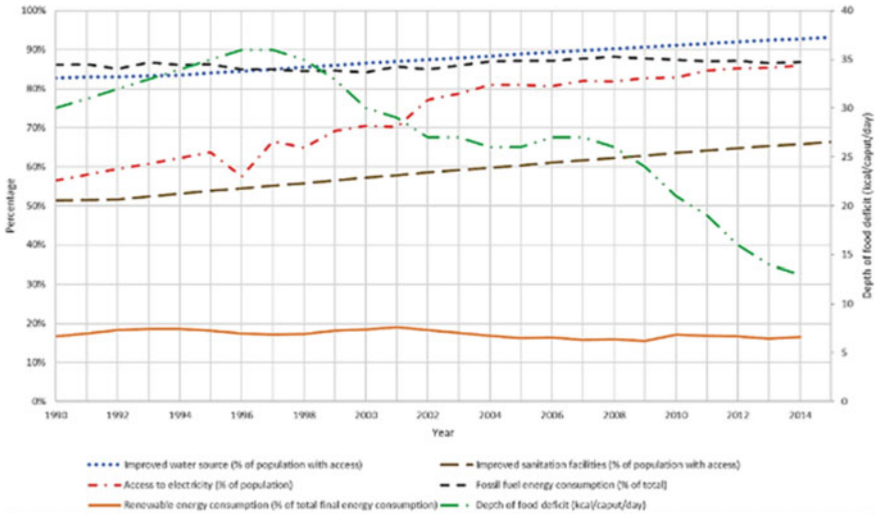

Fig. 2 Annual changes in WEF nexus indicators (improved water source, access to electricity, renewable energy consumption, improved sanitation facilities, fossil fuel energy consumption, and depth of food deficit) from 1990 to 2014 relating to SDGs 2, 6, and 7 over time in South Africa (FAO 2017; The World Bank 2018)

Obstacles to achieving WEF security differ by province. Gauteng is the physically smallest province in South Africa, but includes Johannesburg, the economic capital of the country; the province is home to more than a fifth of the nation's population. Due to isolation from significant water sources, Gauteng imports approximately 88% of its water via various inter-basin transfer schemes. The province contributes approximately 3% of agricultural production but consumes about 20%. Electricity consumption is high South Africa , accounting for 24% of South Africa's total electricity delivered in March 2018 (StatsSA 2018). Electricity for Gauteng is supplied predominantly by coal-fired power stations in Mpumalanga (Von Bormann and Gulati 2014).

The Western Cape Province generates approximately 25% of the agricultural sector's gross income, and exports more than 50% of its produce, 75% of which is destined for European markets. The provincial government has invested significantly to ensure good water quality within this region, as the income from produce exports is between R190 million and R570 million annually (Von Bormann and Gulati, 2014). The sustainability of food exports is controversial, since this practice indirectly exports water from a water-scarce area. The threat of exporting "virtual water" was demonstrated with the drought of 2017–'18 in the Western Cape, including Cape Town. These trade-offs must be studied further from a water perspective to determine the continued viability of fruit and vegetable exports.

In the Karoo, no large-scale electricity generation projects exist; the region relies on small solar farms and access to the national power grid. The energy generation of this region has been the subject of debate, focusing on unconventional energy sources such as shale gas or coalbed methane. Water is required to enable drilling and hydraulic fracturing, and it is a very scarce resource in the arid, semi-desert Karoo, leading to concern about the impact of these energy generation methodologies on the quality and quantity of groundwater. Water resource systems and the supporting infrastructure within the Karoo are already extremely strained: only 14% (16 million m^3) of the storage capacity of the Welbedacht Dam is currently available due to unmitigated siltation (Ololade et al. 2017). Smaller towns in the Karoo generally depend on groundwater supply, which amplifies the potential threat that unconventional oil and gas (UOG) operations present (Ololade et al. 2017).

2 Methodology

A framework for analysis of the WEF trade-offs was developed by stakeholders during a consultative workshop. Existing WEF nexus frameworks were examined to ascertain their applicability to South Africa . Based on the literature review[1], 20 frameworks were identified and screened, leaving 18 frameworks for assessment for their applicability to the WEF ecosystem of South Africa based onAfricamultiple factors:

- Inclusion of all WEF nexus sectors, with equal weight to water, energy, and food;
- Comprehensive consideration of the economic and demographic drivers of change (industrialization, global climate change, population growth, urbanization);
- Applicability to the economic and demographic circumstances of South Africa (based on the above drivers of change);
- Applicability to other socio-economic, environmental, and technical characteristics of South Africa (livelihoods [rural poverty], data requirements, sectoral compartmentalization [governance/policy], fossil fuels, etc.);
- Integration of the framework among the different sectors;
- Breadth of sectors considered, e.g., environment/ecosystems, land, climate change, livelihoods, waste management, recycling/reuse;
- Integration of the SDGs and MDGs; and
- Innovation and infrastructure, e.g., power stations, improved technology.

A ranking template was applied, giving each framework a score (on a ten-point scale) based on its relevance to the established criteria. The South African framework was adapted from the most relevant of the frameworks based on the above-stated criteria. Those selected are discussed in detail in Sect. 3.1.

A specific aim South Africa was to yield a framework linking the WEF nexus to the SDGs, particularly SDGs 2, 6, and 7. Land is a key consideration in South

[1]Search words such as WEF nexus model, WEF nexus frameworks, WEF nexus tools, WEF nexus analytical tools, WEF nexus governance, WEF nexus synergies and trade-offs, WEF nexus sustainability indicators, WEF nexus application, WEF nexus data, WEF nexus operationalisation, WEF nexus case studies, and WEF nexus financing were searched in Google.

Africa, as is Africathe incorporation of innovation in the WEF nexus to supplement advances achieved by just rebalancing among WEF trade-offs, which in itself would be insufficient. Innovation is necessary to ensure resource security, and access to water, energy, and food for all people.

3 Results and Discussion

A wide range of international initiatives exist to analyze the close relationships among the WEF components. The WEF nexus has gained prominence as an approach to consider solutions to global challenges in part because it can be used as an analytical tool, a conceptual framework, and as a basis of discussion and debate (Keskinen et al. 2016). As an analytical tool, the WEF nexus systematically and quantitatively reveals the interactions among WEF resources; as a conceptual framework, it is a pathway to understand WEF linkages, promote coherence in policymaking, and enhance sustainability , and as a discussion platform it is a tool for problem-framing and the promotion of cross-sectoral collaboration (Albrecht et al. 2018). For these reasons, the WEF nexus contributes substantively to understanding the complex and dynamic interlinkages among issues related to the security of water, energy, and food.

3.1 Applicability of Other Existing Frameworks to the WEF Nexus in South Africa

Based on the methodological criteria, five existing frameworks were identified as most applicable and were evaluated.

(a) Smajgl et al. 2016

The study by Smajgl et al. (2016) presents a cross-sectoral, balanced, and dynamic WEF nexus framework where sectoral objectives are given equal weight, revealing the emergences and/or changes in cross-sectoral connections as a result of single sector interventions. The dynamic WEF nexus framework describes interactions between (a) the three sectors and (b) the nexus core and the three sectors (Fig. 3). The nexus core in this framework consists of the major drivers of the water, energy, and food sectors, as well as cross-sector factors.

This framework, however, limits consideration of the interacting variables in the nexus core as it looks at only climate change and population growth as the main drivers of ecosystem services. The framework also displays how sectoral outcomes provide feedback and control core drivers, thereby creating sustained interactions. Three distinct entry points are depicted in the framework, introducing sector-specific interests. This conceptualization coordinates across sectors, to avoid unintended trade-offs and consequences. The framework requires that stakeholders account for sectoral interdependencies.

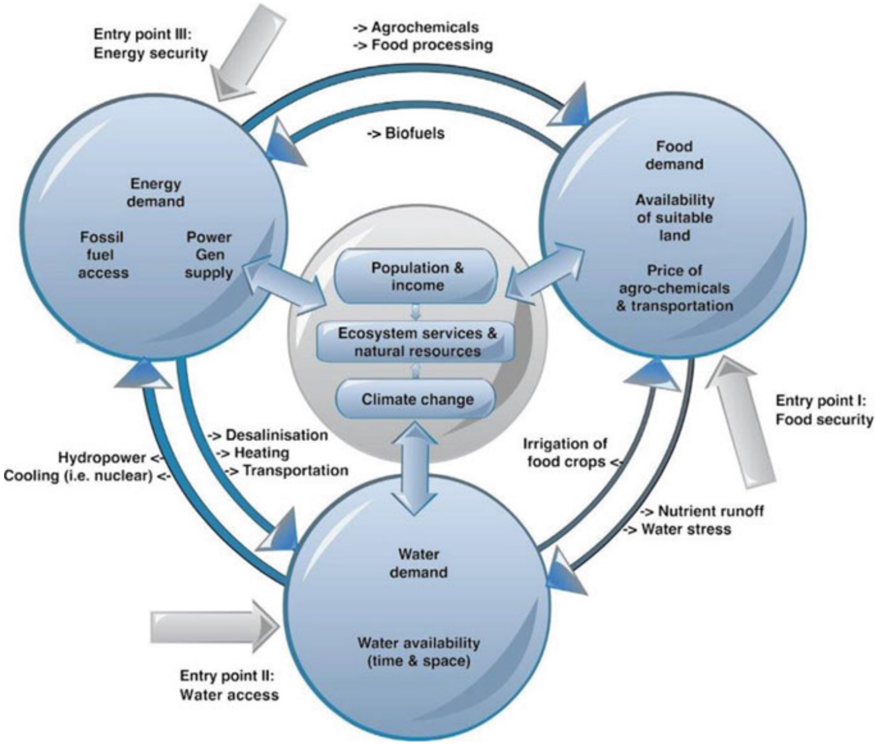

Fig. 3 The energy-water-food nexus presented by (Smajgl et al. 2016)

(b) Ringler et al. (2013)

Ringler et al. (2013) present the concept of the water-energy-land and food (WELF) nexus, emphasizing that this concept plays out differently in various parts of the world. The WELF nexus framework evaluates the linkages that exist among the water, energy, land, and food sectors (Fig. 4). The direct and indirect drivers of change, which affect these linkages, are clearly depicted in the framework. Standard WEF nexus frameworks do not include the land dimension; its inclusion in this framework is recognition of its importance not only in the production of food, but also for water (underground water storage, reservoirs) and energy supply (shale gas or biofuels), as well as shedding light on the importance of land scarcity. In contrast to many WEF nexus frameworks that tend to be water-centric, this framework puts food at the center.

(c) Karabulut et al. (2018)

In this study, a synthesis WELF matrix system describes the complex and closely related relationships among the natural resources used for food (most importantly, water and land), energy, and ecosystems . The matrix can be set for different scales (from global to local) and includes the impacts and nexus with climate change. The

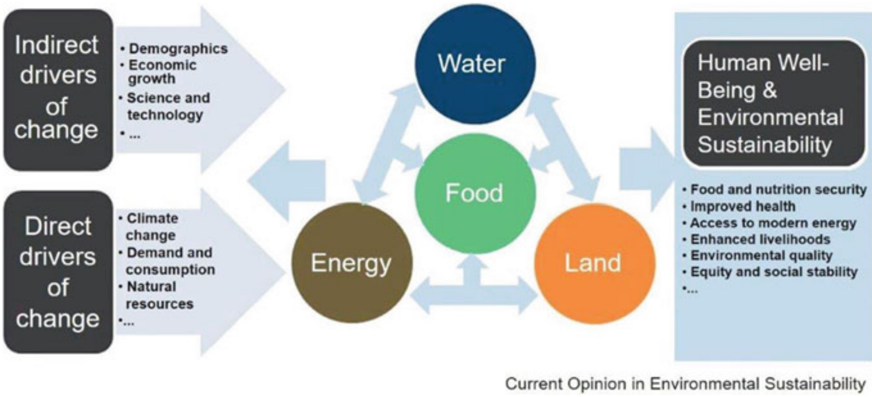

Fig. 4 The extended water, energy, food, and land nexus presented by (Ringler et al. 2013)

aim of the matrix is to integrate quantitative and qualitative aspects, which are often neglected in conventional approaches of impact assessment. Due to the complexity of interactions among the different components, quantitative and expert assessments are both required.

This framework centers on ecosystems (Fig. 5), because they represent all features of water, energy, land and food availability, and production. Land is included within the concept of ecosystems, since the term "land" embraces different land users, land covers, and soil ecosystems. The centrality of ecosystems is also recognized by their incorporation into environmental policies and initiatives internationally. Figure 5 uses three matrices for the WEFL (water-energy-food-land) nexus in the form of a double-entry table to identify relationships among sectoral uses of resources as well as the provision of ecosystem services. Potential service flows are classified according to types/sub-types of sectoral uses, which can refer to either final or intermediate services, with direct or indirect effects on human well-being. The main purpose of this framework is to support a comprehensive nexus approach, called the Ecosystem-Water-Food-Land-Energy (EWFLE) Nexus.

(d) Martinez-Harnandez et al. (2017)

This study, called "NexSym," employs simulation and analytics to depict its Nexus Simulation System. The purpose is to develop a tool for integrated resource assessment, and to account for integration within and across WEF sectors, ecosystems, and consumption components that interact with local systems. A premise of this study (Martinez-Hernandez et al. 2017) is the need for a nexus tool on a local scale, tailored to local conditions to more easily achieve synergistic techno-ecological interactions.

The NexSym software allows users to simulate how a part of a nexus is affected by a change in another part, as well as to evaluate key interactions the synergies of which may be further integrated. It offers a conceptual and modeling framework, taking into account local use of energy, water and food production, and waste treatment, as well as interactions of local components of the WEF nexus, such as ecosystems and

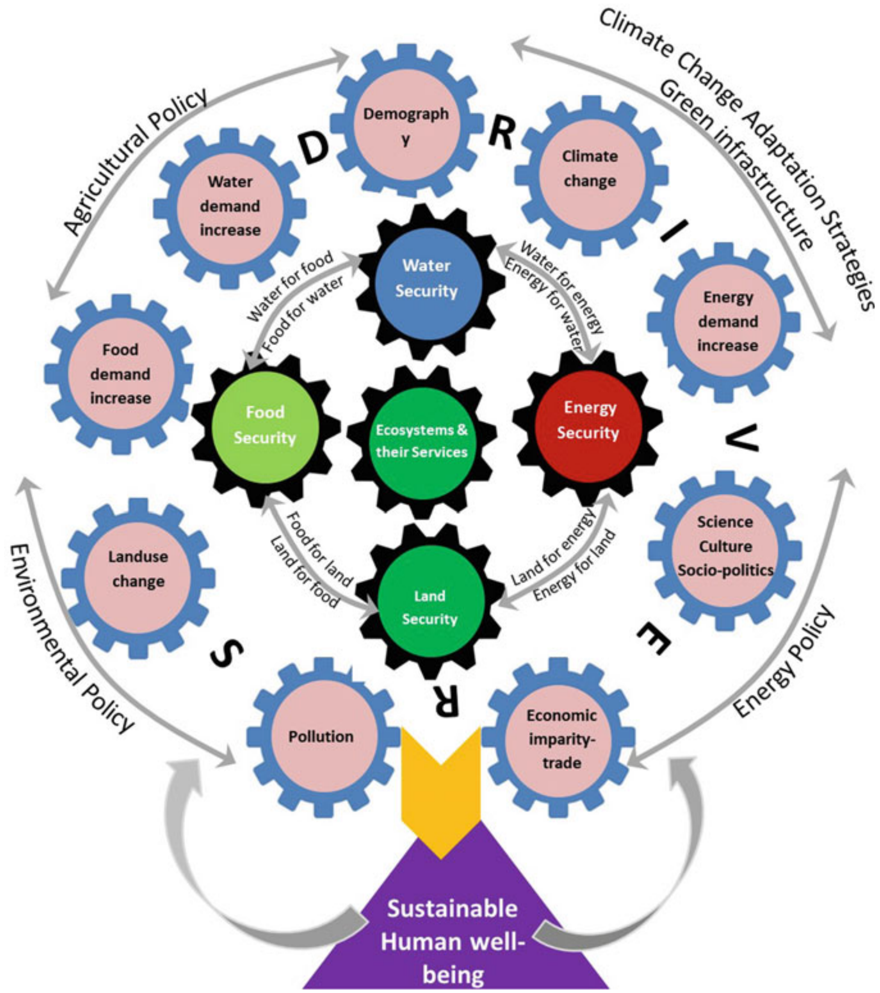

Fig. 5 Framework for the ecosystem-water-energy, land and food security nexus presented by Karabulut et al. (2018)

consumption. The approach combines data inputs, predictive models, and integrated outcome analysis (Fig. 6).

The NexSym models a local WEF system using ecological (managed or natural ecosystems such as heathlands or forests), technological (man-made industrial and municipal facilities), and consumption components ("sinks" of products and services, such as residential and commercial activities). The framework is primarily focused on local systems, and therefore requires detailed input from a subject locale to enable meaningful assessment. The study summarizes its focus by stating that, "engagement

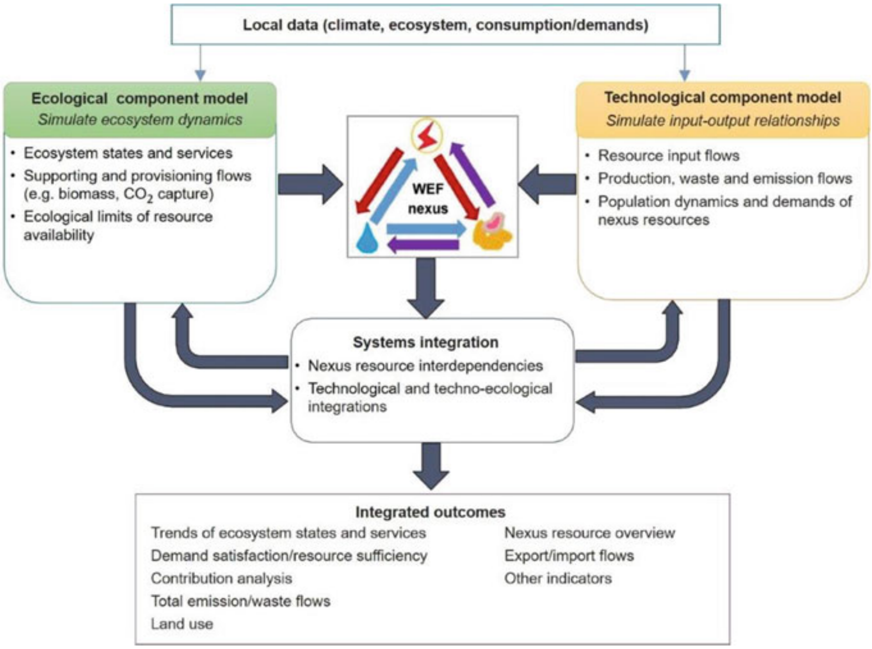

Fig. 6 The NexSym model's intended input, output, and techno-ecological view of the WEF subsystem and their interactions (Martinez-Hernandez et al. 2017)

with researchers and local communities to develop datasets specific to local contexts is crucial for the successful application of the tool."

(e) Conway et al. (2015)

Conway et al. (2015) approach southern Africa's nexus from the perspective of climate, based on a modified Hoff's nexus framework (Hoff, 2011), which integrates global trends (drivers) with actions, to highlight the role of climate as a driver. The framework considers the main elements of intra-regional interdependencies in WEF sectors within each country, while it highlights connections on the river basin scale and draws attention to case studies of specific trade-offs and synergies.

The importance of climate in determining potential agricultural production, medium-term water availability, and some components of energy production and demand are emphasized in this framework. Figure 7 depicts how climatic variability drives fluctuations in WEF elements, with secondary effects on the whole nexus.

3.1.1 Ranking of Frameworks

Table 1 indicates the rankings of the selected frameworks, features of which are used to develop a modified framework for South Africa . Of the 25 identified frameworks,

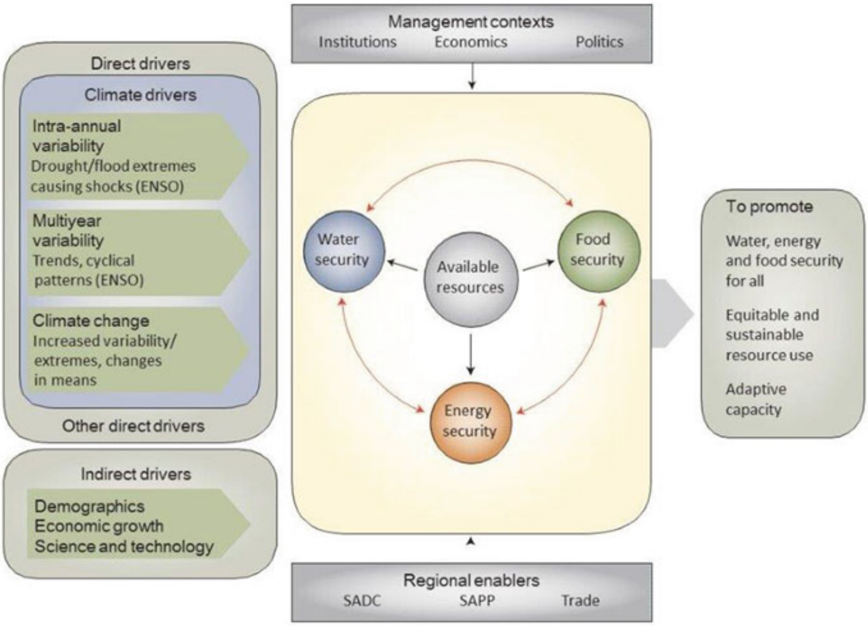

Fig. 7 A modified version of the (Hoff 2011) nexus framework presented by Conway et al. (2015)

only five were sufficiently suitable to the South Africa context using the established criteria (Table 1).

The framework developed by Smajgl et al. (2016) scored relatively well on the "applicability to South Africa" criterion, but was weak Africa in its consideration of innovation.

The next three studies, by Ringler et al. (2013), Karabulut et al. (2018), and Martinez-Hernandez et al. (2017), ranked second through fourth, respectively, in terms of their applicability to South Africa, but would have benefited from South Africa deeper consideration of potential innovation and its connection to the SDGs. The framework by Conway et al. (2015) would have been more applicable to use in South Africa by integrating sectors, acknowledging adjacent sectors (e.g., livelihoods, land, ecosystems), and including innovation. All these shortcomings were accounted for by modifying the selected frameworks for more applicability and relevance to South Africa.

3.1.2 Innovation

South Africa Consideration of innovation encompasses improved infrastructure (e.g., power stations with lower emissions and/or dry-cooled power plants), renewable energy mechanisms (biofuels, wind, tidal, and better exploitation of abundant solar

Table 1 Criteria for ranking the existing WEF nexus frameworks

Framework name	Sectors considered	Scale of application	Sector integration (Y/N)	Weaknesses	Strengths	Score 1—low 5—high
Smajgl et al. 2016	All three	National	Y	None, possibly innovations	Integration, inclusion of SDGs, drivers, and other sectors	5
Ringler et al. (2013)	All three	National	Y	To a small degree, innovations and SDGs	Inclusion of drivers and integration	4
Karabulut et al. (2018)	All three	National	Y	Innovations and inclusion of SDGs	Integration of other sectors and drivers	3
Martinez-Harnandez et al. (2017)	All three	National	Y	Innovations and inclusion of SDGs	Applicability of South Africa and integration	3
Conway et al. (2015)	All three	National	Y	Innovations, other sectors, and integration	Addressing challenges and applicability to South Africa	3

energy), and data generation improvements to support the big data needs to develop useful output to inform decision-making and facilitate data sharing and dissemination. There is also potential to further develop technologies to improve water efficiency (desalination, establishing dry-cooled power plants) and seasonal climate forecasting (climate change for farmers).

3.1.3 Sustainable Development Goals (SDGs)

The WEF nexus is a key tool for regional integration and development of the SDGs, as well as delivery of SDG goals at the national level (Mabhaudhi et al. 2016). SDGs will drive future policies related to the WEF nexus through SDGs 2, 6, 7, 8, and 9.

SDG 2 (zero hunger); SDG 6 (clean water and sanitation); SDG 7 (affordable and clean energy); SDG 8 (affordable work and economic growth); and SDG 9 (industry, innovation, and infrastructure) illustrate how the SDGs connect with the WEF nexus. For example, achieving SDG 2 requires the eradication of food insecurity and improving nutrition. SDG 6 requires basic access to water and sanitation to overcome water scarcity. SGD 7 necessitates the development of greater renewable energy sources, and access to them.

3.1.4 Challenges

The frameworks offered by Karabulut et al. (2018) and Martinez-Hernandez et al. (2017) scored low for the inclusion of key societal challenges and would be strengthened by taking into account livelihoods (rural poverty, high rates of unemployment, barriers to educating the poor, electricity shortages, land issues), nutrition, health and food insecurity (agricultural sector), as well as improving economic growth, water scarcity within the context of climate change, and data requirements and accessibility.

3.1.5 Integration

Conway et al. (2015) had the lowest score for integration among the five top-ranked frameworks; in order to improve its applicability to South Africa, it must account for integration among the three WEF sectors by illustrating how they interrelate, and offer recommendations to improve integration and its potential to enhance livelihoods, land management, environmental ecosystems, climate change resilience, and waste management.

3.2 A Proposed South African-Based WEF Nexus Framework

Figure 8 is a schematic of a proposed WEF nexus framework for South Africa based on the criteria Africa used to select the top five WEF nexus frameworks delineated in Sect. 2.

The work by Smajgl et al. (2016), Ringler et al. (2013), and Karabulut et al. (2018), in conjunction with the work by Hoff (2011), was built upon to design the WEF nexus framework for South Africa. Figure 8 illustrates the vital drivers of change and the biggest challenges facing the country Africa, strongly influencing the WEF nexus. It also illustrates that with proper policies, strategies, and the consideration of alternative clean, renewable options, vastly improved human well-being and environmental sustainability can be achieved. The framework developed for South Africa puts emphasis on SDGs 2, 6, and 7, describing drivers and feedback among these sectors. Direct and indirect drivers of change, which affect these linkages, are also illustrated in the framework (Fig. 8).

3.3 Potential Indices, Metrics, and Models for Evaluating the WEF Nexus

It is imperative to define the priorities, aims, scale of application, and data availability in order to effectively adopt the WEF nexus framework in South Africa (Endo et al. 2017). No one approach is applicable to all situations and the suitability of a given framework or methodology will vary in response to the aims, priorities, and scale of application, from global to local. As one would expect, data requirements and needs for their aggregation and analysis will increase as one move from local to global scale. Likewise, required tools and models increase in complexity from local to global scale (Zhang et al. 2018).

To accurately model and assess the WEF nexus, it is useful to generate data that quantifies flows of energy and materials, makes numerical predictions, and estimates the associated costs (Keairns et al. 2016). When developing or considering models to guide data generation, it is important to restrict scope to the relevant aspects of the WEF nexus to eliminate complexity, but to be aware of risks associated with these omissions and to develop assumptions associated with these risks. All stakeholders must contribute to the assessment process, which will inevitably require trade-offs between indicator-based assessments and quantitative approaches (Keairns et al. 2016).

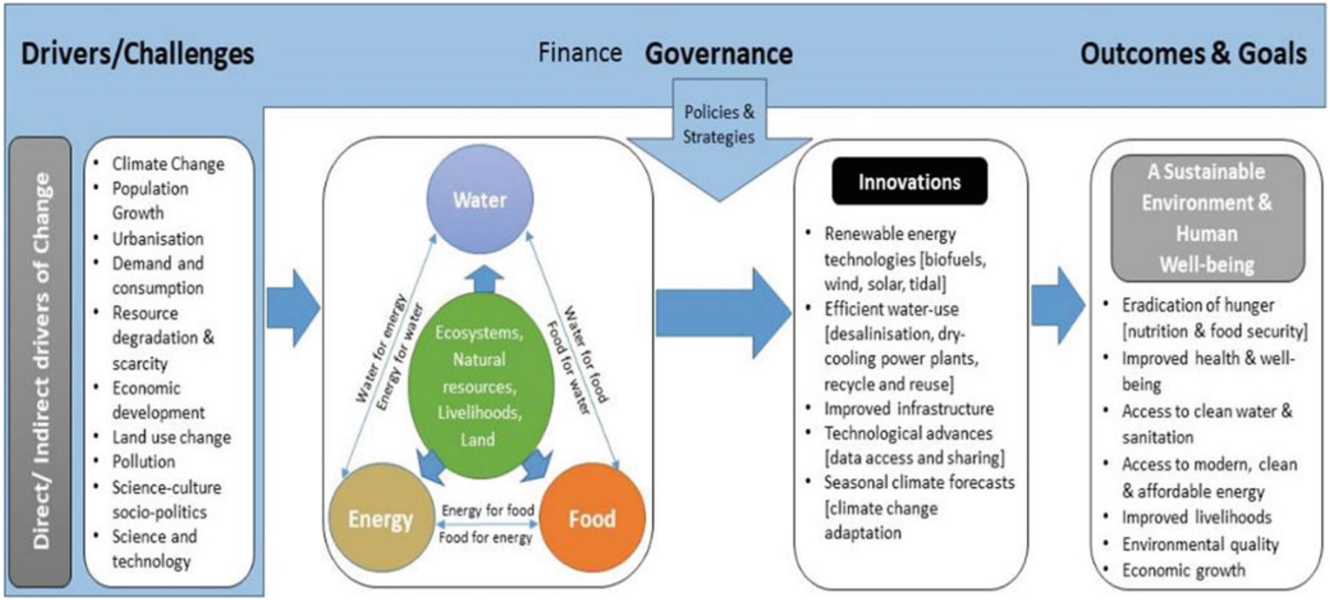

Fig. 8 A Proposed WEF nexus framework for South Africawith particular emphasis on Sustainable Development Goals (SDGs) 2, 6, and 7 (modified based on Smajgl et al. (2016, Ringler et al. (2013), Karabulut et al. (2018) and Hoff (2011))

3.3.1 Tools

A number of indices, metrics, and models can be used to evaluate the WEF nexus. The MuSIASEM (Multi-Scale Integrated Assessment of Society and Ecosystem Metabolism) tool was developed to simulate the WEF nexus by means of depicting the metabolic patterns of WEF in relation to ecological and socio-economic variables. It was originally developed for the energy sector, but can be adapted to the WEF nexus by including water and food in its methodology (FAO 2013). MuSIASEM allows the simultaneous use of demographic, ecological, and social variables even if they were defined on different levels and scales, thus enabling effective analysis of the interdependencies among water, energy, and food at a national or sub-national level. Furthermore, MuSIASEM provides feasibility, viability, and desirability checks of each proposed scenario. It was used to generate an integrated assessment of the contribution and convenience of Concentrated Solar Power (CSP) and woody biomass as alternative sources for electricity production in South Africa (LIPHE4, 2013). This case study uses quantitative data from published research to evaluate electricity consumption in South Africa , as well as production factors of CSP and woody biomass-based electricity. The maximum short-term potential of CSP and woody biomass were calculated to be 3,000 GWh and 5,900 GWh, respectively; their respective input requirements as well as the trade-offs between production factors, such as water and land requirements, are described in Table 2.

The WEF Nexus Tool 2.0 was developed by QEERI to evaluate the water, energy, land, financial, and carbon production requirements for food supply in Qatar (Wicaksono et al. 2017). It is a scenario-based tool created primarily to quantify the resources required for food supply at a national scale; it allows the user to create various scenarios by setting parameters for inputs of water, energy, and foods. In Qatar, it assessed water, energy, and land requirements, carbon footprint, financial cost, energy consumed through import, and carbon emission through import (Daher and Mohtar 2015). Multiple scenarios were generated, with the most realistic scenarios depending on scientific and policy inputs. Assumptions and limitations include the following:

- Food products assessed are only agricultural crops and exclude meat, dairy, etc.
- There is no calculation of water and soil quality.
- Relationships among system components are based on empirically based data.
- The tool assumes linear relationships among systems.
- Projections of prices, population growth, and resource demands are not included.

Table 2 Requirements of production factors for scenarios concentrated solar power (CSP) and woody biomass-based electricity (LIPHE4, 2013)

Scenario	Labor (Mhr/y)	Water (hm^3/y)	Land (ha)
CSP	2.7	9.1	5 100
Woody biomass	120	NA	9 241 000

- It does not capture the financial costs associated with the use of different water and energy sources.

The WEF Nexus Tool 2.0 represents an opportunity to develop a tool for South Africa specifically. It may be further improved by including prediction analyses of population growth, resource demand increase, and financial considerations.

The water and energy nexus is applied to a Sankey diagram (Fig. 9) that quantifies flows in each stage of the water and energy supply chains (Hu et al. 2013). The diagram depicts the water-energy nexus at a household scale in Australia (Kenway et al. 2013), a regional scale in China (Hu et al. 2013), and a national scale in the USA (USDoE, 2014). More recently, it was used to generate the relationships among water, energy, and food for the United Kingdom at a capital, government, and household levels, using multiregional input-output (MRIO) databases, as can be seen in Fig. 9. If applied to South Africa, it would provide a graphical representation of the complexity of the interlinkages among water, energy, and food. The Foreseer Tool (https://www.foreseer.group.cam.ac.uk) can be used to create Sankey diagrams.

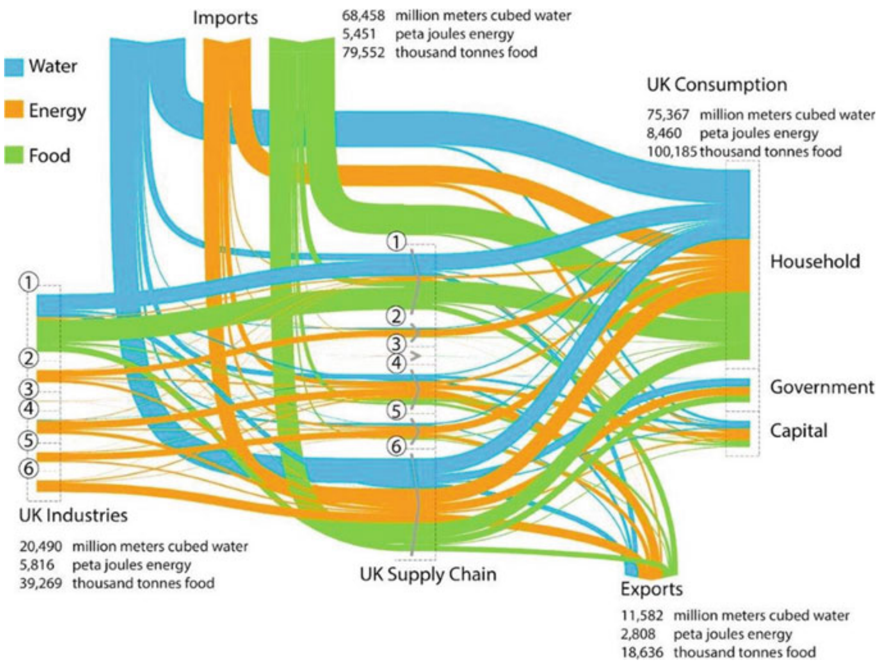

Fig. 9 Sankey diagram showing water, energy, and food flows, from industry to final consumption for the UK in 2013, where 1 = agriculture and food processing, 2 = power generation and distribution, 3 = primary material industries, 4 = manufactured goods and recycling, 5 = transport, 6 = other services (Owen et al. 2018)

3.3.2 Indices

The Nexus City Index (NXI), developed by the United Nations, considers food, energy, and water resources and includes an equity index. The UN-Habitat approach forms the basis for NXI and offers indices to monitor the development of productivity, infrastructure development, quality of life, equity, and environmental sustainability. The approach is based on urban resilience, which is targeted in Goal 11 of the SDGs (Schlör et al. 2018). Along with the NXI_{region}, the World City Prosperity Index, the Regional City Prosperity Index, and the Regional City Index (NXI_{city}) were developed to assess the resilience of various regions and cities in the world (Schlör et al. 2018). They provide data to support decision-making to identify, monitor, plan, and manage urbanization in cities and regions, with special attention to developments within the WEF sectors (Schlör et al. 2018). These indices are useful for South Africa, but do not consider policy implications, nor do they include scenario-based predictions of population growth, climate change, or economic growth.

3.3.3 Models

The South Africa TIMES model (SATIM-W) tool considers trade-offs between water and energy systems for cost-effective sustainable planning (Ahjum et al. 2018). As the name suggests, it is specific to South Africa and incorporates large amounts of quantitative data relating to the country's water supply, usage, and costs (including water quality and treatment). Scenarios include climate change impacts, economic growth, local environmental best practice, policy compliance, and low carbon technologies (Ahjum et al. 2018). To address the hydrological gaps of the model, the World Bank, with the SADC secretariat, has launched a project to build sustainable groundwater management in the region (The World Bank, 2016). This model may be altered to include the food sector of the WEF nexus as well as social aspects; it has great potential to effectively evaluate the WEF nexus in South Africa.

A new model for integrated assessment of global change (ANEMI) was established as an integrated assessment model to simulate all relevant variables, including climate, the carbon cycle, the economy, population, land use, the hydrological cycle, and water demand and quality (Davies and Simonovic, 2011). It emphasizes the interconnections and feedback of each element, and is a significant improvement over previous models because it includes food production and considers factors that optimize the energy-economy factor (Akhtar et al. 2013).

Ozturk (2017) formulated simple non-linear regression equations using a set of explanatory variables of agricultural sustainability to create an understanding of the water-energy-food nexus within six sub-Saharan African countries. The study utilized three panel regressions, including the least squares regression ("common constant method"); fixed effects ("least squares dummy variables"); and the random effects model ("Dynamic Model").

The Climate Land-use Energy and Water Strategies (CLEWS) modeling framework integrates existing models and systems, such as Water Evaluation and Planning (WEAP), Long-range Energy Alternatives Planning System (LEAP), and Agro-ecological Zoning (AEZ), by simulating and comparing data among them in multiple iterations to find a convergent solution (Keairns et al. 2016). It analyzes interlinkages among resource sectors to determine the effect that one sector might have on the others, and identifies counterintuitive findings in these integrated systems. It is a free online tool that creates scenarios based on (UN DESA 2013):

- Global estimates of CO_2 emissions, water use, and investment in energy and material production.
- Estimates of CO_2 emissions and water use by energy source.
- Estimates of mix of energy supply.

This model has been applied to a case study in Mauritius, focusing on two policy goals: renewable energy production and renewable fuel standards that mandate the blending of ethanol into gasoline. Similarly, case studies for Kenya and Bolivia investigated SDG 7 (energy access to all). This model may be adaptable to South Africa ; however, it is mainly limited to the energy sector.

Simpson and Berchner (2017) propose to develop a composite indicator to report on the WEF nexus. Their study highlights that indices should be based on quantitative data and represented by a single numeric value, for consistency among evaluations of different cities and countries. Mitigation scenarios could be tested to ensure the establishment of achievable and measurable goals to improve the WEF nexus index over time.

For all these and any tools, models, and indices, data storage and accessibility will play a significant role in understanding and analyzing the WEF nexus. It is also important to consider temporal and spatial scale differences of different elements, suggesting the need to integrate multiple available models and tools, as well as input from stakeholders and policymakers. Table 3, adapted from Martinez-Hernandez et al. (2017), summarizes key models and indices that may be used for evaluation.

4 Conclusions

A WEF nexus framework for South Africa is urgently required so that it can be applied as a tool for resource management to optimize benefits and minimize conflicts. Water, land, and energy resources in South Africa are highly emotional issues and therefore must be approached and managed judiciously; the WEF nexus offers such an opportunity. An understanding of the WEF nexus in South Africa is of great value when developing a framework that is specific for the country.

The WEF nexus framework was developed with emphasis on Sustainable Development Goals 2 (zero hunger), 6 (clean water and sanitation), and 7 (affordable and clean energy). Its framework considers the importance of livelihoods and human well-being and eminent threats to sustainable development, especially in South

Table 3 Potential models and indices that could be used to evaluate the water-energy-food nexus in South Africa, adapted from Martinez-Harnandez et al. (2017)

Tool	Modeling framework	Scale	System breadth	Analytical capability	Flexibility	Applicability to WEF nexus in South Africa
GLOBIOM	Dynamic multiregional partial equilibrium model	Global	WEF nexus and other interacting systems such as ecosystems	Geographically explicit and long-term management of global land uses	Focused on land uses	No, only applicable at a global scale
WEF Nexus Tool 2.0	Input-output	National	WEF nexus components	Scenario-based for given food self-sufficiency level calculates nexus resource flows and interactions, and greenhouse gas (GHG) emissions	Focused on food as entry point and Qatar country	Yes
MuSIASEM	Input-output, nested hierarchical view of the economy	Aggregated to national or sub-national level	WEF nexus components, land, economy, human capital, and ecosystems	Accounting of flows and funds and their ratios as indicators. GHG emissions and land use	Adaptable to various contexts	Yes, it has already been applied to South Africa
CLEWS	Integrates detailed models from different tools (including WEAP, LEAP, and AEZ)	National	Climate, land, energy, and water	Depend on the tools used for the CLEW assessment	Depend on the tools used for the CLEW assessment	Yes, if the model can be changed to evaluate the inter-sectoral influences of the WEF nexus components

(continued)

Table 3 (continued)

Tool	Modeling framework	Scale	System breadth	Analytical capability	Flexibility	Applicability to WEF nexus in South Africa
Quantitative assessment framework	Input-output based on Lontief matrices	National	WEF nexus components	Scenario-based, accounting of nexus resource consumption, and interdependency indicators	Fixed defined technologies and interactions	Yes, could be extended to analyze the influence of socio-economic factors
DEA	Data envelopment analysis model	Local (city level)	WEF nexus components	Input-output efficiency		No, cannot be used for national evaluation of the WEF nexus
PRIMA	Integrates regional climate, hydrology, agriculture and land use, socioeconomics, and energy systems sector models	Regional	WEF components, economy, land use	Climate change related analyses and costs, land use, greenhouse gas emissions	Flexible, portable, and modular	No, only relevant for regional decision-making
ANEMI	Integrated assessment model	All scales	Climate, carbon cycle economy, population, land use, hydrological cycle, and water demand and quality	Reveals the interconnections and feedback of each element	System dynamic simulation	Yes
Sankey diagram	Graphically represents the complex conversion pathways, flows, and interdependencies between variables	All scales	WEF nexus components	Based on the data input	Adaptable to various contexts	Yes

(continued)

Table 3 (continued)

Tool	Modeling framework	Scale	System breadth	Analytical capability	Flexibility	Applicability to WEF nexus in South Africa
Nexus City Index	Measures the prosperity and sustainability of the FEW nexus for 69 cities	All scales	WEF nexus component, prosperity	A top-down urban WEF nexus approach which aggregates the WEF sectors to a single indicator	Flexible, and includes likewise indices World City Prosperity Index, the Regional City Prosperity Index, and a regional city index	Yes
Message	Modeling potential future energy scenarios	Global and Regional	Energy and greenhouse gas emissions	Dynamic linear programming model and can be linked with MAGICC (a separate program for predicting GHG-induced climate change) and GLOBIOM		No, does not consider all WEF nexus components

Africa . Current literature shows that policies, strategies, and plans have not fully embraced the applicability of the WEF nexus to sustainable resource management. More research is needed and must include participation of policymakers, researchers, and other stakeholders to provide a comprehensive perspective on the desirability of and approach to implementing the WEF nexus in South Africa.

The most relevant and applicable indices , models, and metrics relating to the WEF nexus in South Africawere reviewed and summarized. Most would require modifications to be applicable to South Africa. Data availability and quality will be a factor in the reliability of any model, emphasizing the necessity of a central database where data can be compared and validated. Temporal and spatial scale differences among data inputs also require further consideration and may be best resolved by integrating multiple models and tools.

References

Ahjum F, Merven B, Cullis J, Goldstein G, DeLaquil P, Stone A (2018) Development of a national water-energy system model with emphasis on the power sector for south africa. Environ Progr Sustain Energy 37:132–147

Akhtar MK, Wibe J, Simonovic SP, MacGee J (2013) Integrated assessment model of society-biosphere-climateeconomy-energy system. J Environ Model Softw 49:1–21

Albrecht TR, Crootof A, Scott CA (2018) The water-energy-food Nexus: A systematic review of methods for nexus assessment. Environ Res Lett 13:043002

Carter S, Gulati M (2014) Climate change, the food energy water nexus and food security in South Africa. Understanding the Food Energy Water Nexus. WWF-SA, South Africa. http://awsassets.wwf.org.za/downloads/1__a16231_wwf_climate_change_few_and_food_security_in_sa__online.pdf

Conway D, Van Garderen EA, Deryng D, Dorling S, Krueger T, Landman W, Lankford B, Lebek K, Osborn T, Ringler C (2015) Climate and southern Africa's water–energy–food nexus. Nat Clim Change 5:837

Daher BT, Mohtar RH (2015) Water–energy–food (WEF) Nexus Tool 2.0: guiding integrative resource planning and decision-making. Water Int 40:748–771

Davies EGR, Simonovic SP (2011) Global water resources modeling with an integrated model of the social–economic–environmental system. Adv Water Resour 34:684–700

Endo A, Tsurita I, Burnett K, Orencio PM (2017) A review of current state of research on the water, energy and food nexus. J Hydrol Region Stud 11:20–30

FAO (2013) An innovative accounting framework for the food-energy-water nexus. Application of the MuSIASEM approach to three case studies

FAO (2017) Food security indicators. Vol. 2018

Hoff H (2011) Understanding the nexus: Background paper for the Bonn Nexus Conference. SEI

Hu G, Ou X, Zhang Q, Karplus VJ (2013) Analysis on energy–water nexus by Sankey diagram: the case of Beijing. Desalin Water Treat 51:19–21

Karabulut AA, Crenna E, Sala S, Udias A (2018) A proposal for integration of the ecosystem-water-food-land-energy (EWFLE) nexus concept into life cycle assessment: a synthesis matrix system for food security. J Clean Prod 172:3874–3889

Keairns DL, Darton RC, Irabien A (2016) The Energy-Water-Food Nexus. Annu Rev Chem Biomol Eng 7:239–262

Kenway S, Scheidegger R, Larsen TA, Lant P, Bader HP (2013) Water-related energy in households: a model design to understand the current state and stimulate possible measures. J Energy Build 58:378–389

Keskinen M, Guillaume JH, Kattelus M, Porkka M, Räsänen TA, Varis O (2016) The water-energy-food nexus and the transboundary context: insights from large Asian rivers. Water 8:193

LIPHE4 (2013) The Nexus between energy, food, land use, and water: application of a multi-scale integrated approach South Africa case study, vol 2018

Mabhaudhi T, Mpandeli S, Madhlopa A, Modi AT, Backeberg G, Nhamo L (2016). Southern Africa's water-energy Nexus towards regional integration and development. Water 8

Martinez-Hernandez E, Leach M, Yang A (2017) Understanding water-energy-food and ecosystem interactions using the nexus simulation tool NexSym. Appl Energy 206:1009–1021

Nhamo L, Bekithemba B, Nhemachena C, Mabhaudhi T, Mpandeli S, Matchaya G (2018) The water-energy-food nexus: climate risks and opportunities in Southern Africa. Water 10

Ololade OO, Esterhuyse S, Levine AD (2017). The water-energy-food Nexus from a South African perspective. In: Water-energy-food Nexus. John Wiley & Sons, Inc, pp 127–140

Owen A, Scott K, Barrett J (2018) Identifying critical supply chains and final products: An input-outputapproach to exploring the energy-water-food nexus. Appl Energy 210:632–642

Ozturk I (2017) The dynamic relationship between agricultural sustainability and food-energy-water poverty in a panel of selected Sub-Saharan African Countries. Energy Policy 107:289–299

REDIS (2018) Location and contracted capacities of renewable energy projects in South Africa, vol 2018. Deparment of Energy, South Africa

Ringler C, Bhaduri A, Lawford R (2013) The nexus across water, energy, land and food (WELF): potential for improved resource use efficiency? Curr Opin Environ Sustain 5:617–624

Ross ML (1999) The political economy of the resource curse. World Polit 51:297–322

Schlör H, Venghaus S, Hake J-F (2018) The FEW-Nexus city index measuring urban resilience. Appl Energy 210:382–392

Simpson G, Berchner M (2017) Measuring integration towards a water-energy-food nexus index. Water Wheel 16:22–23

Smajgl A, Ward J, Pluschke L (2016) The water–food–energy Nexus-Realising a new paradigm. J Hydrol 533:533–540

StatsSA (2018) "Electricity generated and available for distribution (Preliminary). South Africa, Pretoria

The World Bank (2016) Southern Africa energy-water Nexus

The World Bank (2018) Indicators, vol. 2018

UN DESA (2013). Global climate, land, energy & water strategies, vol. 2018

UNEP (2016) Global material flows and resource productivity. An Assessment Study of the UNEP International Resource Panel, Paris

USDoE (2014) The water-energy Nexus: challenges and opportunities. Washington

Von Bormann T, Gulati M (2014) The food energy water Nexus: understanding South Africa's most urgent sustainability challenge. South Africa

Wicaksono A, Jeong G, Kang D (2017) Water, energy, and food nexus: review of global implementation and simulation model development. Water Policy 19:440–462

Zhang C, Che X, Li Y, Ding W, Fu G (2018) Water-energy-food nexus: Concepts, questions and methodologies. J Clean Prod 195:625–639