

# Water–Energy–Food Nexus: A Focused Review on Integrated Methods <sup>†</sup>

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**Abstract:** The study of the water–energy–food (WEF) nexus has received increasing attention by the science community and related stakeholders on a worldwide scale, focusing on how these three elements can interact sustainably. Even though many research papers, indices and tools have been recorded, the understanding of interconnection among the elements of the WEF nexus still remains elusive. The aim of this research is to investigate the progress that has been made in the development of methods and tools studying the interconnection between the three resources, namely, water, energy and food. A concise and focused review is carried out, highlighting the parameters and the key stakeholders as evidenced by various approaches. In addition to the optimisation methods and tools that have already been applied in specific problems, special focus is also given to the indicators used in reference to their spatial and temporal dimensions.

**Keywords:** water–energy–food nexus; performance indicators; interconnections; optimisation tools

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## 1. Introduction

In light of the imperative social pressure for sustainability, the connection and synergies between various systems and processes have gradually become necessary to deal with. This presupposes a systemic understanding and study of all the existing resources and technological options and the way they interact, in line with the European Union’s clean energy policy, striving for environmental protection and pollution prevention in an integrated way. In this respect, water, energy and food resources and the related sustainable goals are part of the global discussion agenda that aims to minimise worldwide hunger effects while also improving the economy [1,2]. Water, energy and food are complex resources to manage, with strong interdependencies and critical ladders of end-users, making the decision-making process quite complex in current day as well as in the future, because, as Shannak states [2], ‘water is needed to produce energy, energy is needed to extract, distribute and treat water and food production requires both water and energy’. It is worth pointing out that all people individually are in vital need of these resources daily, with the competition in water use for food and energy security constituting a core problem observed by the water–energy–food nexus (WEF) debate [3].

The WEF nexus is a unifying way of planning and managing these resources, which are multifaceted and at different levels of planning and timescales. Modelling these resources in an integrated way is an assignment requiring the consideration of a wide set of parameters, thus making the optimisation of the WEF nexus intriguing [4].

Following this, the aim of this research is to investigate the progress that has been made in the development of methods that study the interconnection between water, energy and food. Therefore, a concise and focused review is elaborated, highlighting the parameters and the stakeholders of the various approaches. In addition to the optimisation methods and tools that have already been applied in specific problems, special focus is given to the indicators used as performance measures, also in reference to their spatial and temporal dimensions.

## 2. Methods and Tools

The explicit connection between water, energy and food as a system is still ambiguous. However, many frameworks and methodologies have been introduced, allowing partial interpretation of the WEF nexus. Following the constant increase in interest in the WEF nexus, many methods have been published, but with focus on the water attribute. According to the existing literature, different methods are employed, using multiple data demands, merits and challenges, with some of them only taking effect in a specific area, for instance, country or city [5]. In order to gain a better understanding of the coactions and trade-offs in the WEF nexus, a special focus on the interlinkages is needed, as these interlinkages remain a challenge. According to our research, there is a significant number of papers that introduce the most recent methods in the fields [5]. What is worth mentioning is that the methodologies presented in the reviewed case studies are significantly complex and particular; thus, they are not easy to use on a comparative basis.

In terms of tools, several have been developed and used so as to depict the interconnection of the resources as a system. Many researchers, also global non-for-profit organisations, such as IRENA (International Renewable Energy Agency), UN(United Nations) and FAO (Food and Agriculture Organization), have introduced the nexus in the context of a review in order to present different optimisation and modelling tools used in specific case studies, highlighting how to integrate water, energy and food in the aspect of the nexus. In this section, a description of some of these tools is introduced [4–8]. The tools listed in Table 1 were selected after satisfying the following criteria: they include all three nexus resources; they have been published at most during the last 10 years; and they are still active (in use by other users).

In regard to the listed tools, quantitative tools can offer further insight into the nexus, thus simplifying the suggestion for policies and also offering a guidance to stakeholders in order to turn them in sustainable and environmental-friendly solutions. According to IRENA's report, "Renewable Energy in the Water, Energy, and Food Nexus", two "simple nexus tools", as they are characterised by IRENA, are introduced: the WEF Nexus Rapid Appraisal tool, which was developed by the FAO organization and the WEF Nexus 2.0 Tool, developed by Daher and Mohtar [9]. Nevertheless, it has been rather difficult to develop and implement the tools, mainly because of their complexity and high cost in dataset access. Therefore, when planning to resolve challenges, stakeholders need to provide data for these resources in order to develop the necessary connections and trade-offs that are tangled in the water–energy–food nexus [4].

Most of the tools listed below are used to evaluate the transversal trade-offs in regard to water, energy and food and also account system externalities such as changes in climate and population increases. What is worth mentioning is that risk assessment is frequently omitted, as only two of the tools presented in Table 1 use the "risk-informed planning" method, which can help stakeholders form flexibility and reform the appropriate policies [4].

## 3. WEF Nexus Indicators

Indicators are forms of performance measures being defined in any system, regardless of how complex they are [10–13]. A bibliographical research on recent papers has been conducted to identify the indicators used in the integration of the WEF nexus. The resources used for our research have been limited only to those that referred to the integration of the three elements, namely, water, energy and food. The time period that has been taken into account is the last 10 years and, more specifically, after the year 2011 when the Bonn conference took place, as it was the first time the concept of the

WEF nexus was introduced. The latter has actually defined a milestone for WEF nexus thinking, and many studies have been carried out after the congress in the content of the nexus.

**Table 1.** Available methods and tools for the WEF (Water, Energy, Food) nexus based on the research made by Dargin et al. and Dai et al. [9,11].

Tool	Aim/Goal	Method	Software and Developer	Reference
WEF Nexus Rapid Appraisal	Indicator and index sets	Integration tool	Online tool; FAO	[4,10]
World Bank Climate and Disaster Risk Screening Tools	Diagnostics	Risk-informed planning	Open-source tools; World Bank	[4]
ISDG (Integrated Sustainable Development Goals) Planning Model	Scenario making and forecasting	Integration tool	Simulation tool; Millennium Institute	[4]
WEF Nexus Tool 2.0	Scenario making and forecasting	Integration tool	Online tool; (Daher and Mohtar, 2015)	[9]
MuSIASEM(Multi-Scale Integrated Analysis of Social and Ecosystem Metabolism)	Scenario-builders, forecasting and back-casting	Integration tool	Free online tool; FAO	[4,11]
CLEWS(Climate, Land-use, Energy – Water Strategies)	Indicators and indices, scenario making and forecasting	Integration tool; Risk-informed planning	Open source tool OSeMOSYS; (Open Source Energy Modelling System); developed by KTH-Royal Institute of Technology in Stockholm	[4,11]

Proceeding to the analysis of the reviewed papers, the footprint indicator has been one of the most commonly met in the WEF measurement, with the majority of the research works focusing solely on one element/resource (water or energy or food) so as to conclude the highest possible amount of solid evaluation results of the nexus output [12–15]. Even though the studies considering all three elements and adapting “nexus thinking” are still limited in number, as De Vito et al. [14] state, embracing WEF holistic assessment can “reveal the integrated nature” of it.

In parallel, other researchers focused on the sustainable development goals (SDGs) as a response to the policy makers’ need to achieve SD goals in the near future worldwide. Thus, WEF nexus indicators have been adopted in order to monitor the progress in meeting these goals [16,17]. These papers focus on the security of resources and choose to present indicators that could accomplish the various sustainability development goals [17].

In the notion of nexus security, some studies also present indices that can be used in policy analyses. However, Venghaus and Dieken [18] point out that, ‘establishing and using a nexus index has its own difficulties, where the methodology is depending on assumptions that may have a huge influence in the results’. To date, many indices have been recorded, and in Table 2 an illustrative set of those most commonly met is listed.

Finally, some flow indicators have also been found to be in use in studies regarding the WEF nexus. These indicators quantify the flow of the resources across a certain system and, more precisely, they examine and determine the input–output flows of resources used (water, energy, food) in a system. They examine the flows between water, energy and food that are interdependent and measure the sum of the resources used across a system.

**Table 2.** Nexus security indices [18–20].

Index	Description	Developer	Data	Reference
SDG (Sustainable Development Goals Index)	Quantitative model, developed by UN Statistical Commission from the SDG indicators	Sustainable Development Solution Network and Bertelsmann Stiftung	OECD, WHO, UNICEF, World Bank	[18–19]
RAND (Research and Development)	Quantitative model, calculated from three sub-indices which at the same time compose at least two indicators	RAND Corporation	FAO, EIA	[20]

<sup>1</sup> Energy Information Administration (EIA), World Health Organization (WHO), United Nations Children’s Fund (UNICEF).

As previously mentioned, an increase in WEF studies was observed after the Bonn conference in 2011. Most of the studies have been carried out with a view of resolving security and sustainability challenges. These studies have in common the usage of indicators that can address these challenges (security and sustainability) in water, energy and food sectors. The main data that are used for these indicators are retrieved from different websites that examine the nexus system either in the context of a study and/or for policy-making purposes. Moreover, information sources typically include statistical books, national and international databases and survey data. For instance, as far as international databases are concerned, data have been retrieved from the World Bank, FAO, Aquastat, Eurostat etc. [21].

In summary, as a result of the research that has been made, Table 3 presents a ratio of some water–energy–food indicators used from researchers so as to unravel the main research trends of the WEF nexus and allow for the measurement of these resources in complex systems.

#### 4. Implementation Challenges

Although, “nexus thinking” has been widely spread, many challenges have been identified in implementing the evaluation of the interconnection of the three elements of the nexus. One of the most important identified challenges is the feasibility of a solution that contributes to the cohesion of these three resources at the same time [22–24]. Even though many papers and researchers have made a leap of faith in the progress of the nexus, the whole notion of the water–energy–food nexus is still not widely applied [25].

Currently, due to the innovative nature of the issue, investors, policy-makers and individuals related to the water–energy–food nexus concept are provided with the opportunity to introduce/and or establish methods and tools that could estimate the interconnections and related trade-offs. To this extent, the tools are helping in recognising the relevant challenges and diminishing the risks of investments related to the WEF infrastructure [26]. In addition, the fact that the majority of the already-established frameworks for the WEF nexus, as Sukhwani et al. [25] state, ‘are not intended to be used at the local or regional levels as they do not incorporate the proper temporal and spatial scales’ is widely acknowledged. In order to make the interlinkages more understandable, the need for integrated models to investigate them is essential. The tools aiming to that end are limited to only one element of the nexus system [26–28].

**Table 3.** Selected Water–Energy–Food indicators and ratios [16,17,20,29].

Indicator	WEF	Definition	Ratio	Unit	Ref.
Land use	Food	Allocation of agricultural and forest land at national, regional and global level	16.67–58.11	%	[29]
Cereal yield	Food	Cereal production efficiency for the evaluation of countries	291–6037	Kg/ha	[16]
Food security	Food	Food availability and access for all	0.8–6.5	%	[17]
Food sub-index	Food	Food availability and access of sufficient food supplies meeting basic nutritional requirements and quality food for people to meet their notional needs	0.4–0.7	-	[20]
Crop water productivity	Water	Water used for agriculture	0.51–1.42	Kg/m <sup>3</sup>	[16]
Annual freshwater withdrawal for agriculture	Water	Freshwater withdrawals for agriculture	0.3–87.8	%	[16]
Water security	Water	Water accessibility and availability for all	0.123–0.868	-	[17]
Water sub-index	Water	Water accessibility, availability and capacity are equally important and non-compensatory	0.5–0.9	-	[20]
GHG (Greenhouse Gas) emissions (agri-sector)	Energy	Total share of greenhouse gas emissions	4.29–29.53	%	[29]
Energy consumption for crops	Energy	Energy consumed for crop production	39–55	TJ	[29]
Energy security	Energy	Energy accessibility and availability for all	0.124–0.932	-	[17]
Energy sub-index	Energy	Energy availability that meets the needs of residence to promote human development and energy accessibility to modern forms for all	0.3–0.9	-	[20]

Furthermore, governments have not focused on the interlinkages of these three elements (water, energy, food) as a whole, with the authorities' responsibilities usually splitting among different ministries. On the other hand, investors are not attracted to using integrated methods like the WEF nexus because existing subsidisations do not focus on the nexus as one system—rather, in most of cases, they are sector specific.

It is important to point out that this kind of approach is also not popular in private and/or public investments, as the information reaching the wider public (by mass media i.e., newspapers, forums etc.) is still reluctant in regard to focusing on the integrated WEF nexus. This may fall under the issue of complexity and difficulty in communicating the particular notions explicitly to a considerably diversified audience [27], rendering the WEF research area very challenging [28].

## 5. Conclusions

Notwithstanding the fact that the WEF nexus has advanced through the years since the Bonn conference in 2011, the theory-to-practice transcription has not yet been achieved. The present work highlights this by presenting relevant methods, tools and the level of trade-offs identified in the interlinkage of the three elements: water, energy and food. A fundamental cause for this is the lack of thought and in-depth understanding of the interconnection as well as the lack of available (quantitative) data relates to the interlinkages between these resources in order to provide the means to researchers and decision-makers to clarify the links across the three resources in “nexus thinking”.

Regardless of the continuing global interest in the Nexus, the interpretation of the interconnections of these elements remains limited, and this been proved by the number of studies that still focus on only one element among water, energy or food to explore the Nexus, instead of finding new methods and tools to interrelate all the WEF elements.

While the literature carries on to praise enthusiastically the merits of the Nexus, there is a need to make a step forward so as to establish new holistic frameworks of approach that, together with adequate data, can interlink these three resources and also ensure that they are useful to all present and future researchers.

However, it is a great challenge to make a leap of faith in Nexus thinking and collaborate in systematically and constructively ways for the nexus’ system evaluation—not only for the academic community but also for public authorities, private stakeholders and society as a whole, for which assessment of the WEF nexus is critical.

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