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Decision-making tools for sustainable planning and conceptual framework for the energy–water–food nexus

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Abstract

The impact assessment of energy strategies, more specifically those that promote an integrated approach on resource management in other sectors such as water and food, requires knowledge related to the evaluation of the quality and knowledge that may be estimated by quantitative means. The present paper makes inquiries into those knowledge requirements in addition to review the means used to obtain it—including the required entries and the results they provide. In response to the recognized problems in knowledge, this paper introduces a basic reference structure underlying a system to evaluate the way that a progressive development of inexhaustible energies in a particular geographical region can affect the demand of water and food. Then, the proposed conceptual framework constitutes a novel approach for energy policy makers which only consider partial impacts of the energy management. By considering the nexus of energy, water and food, energy management policies may be redefined and differences with current policies must be investigated.

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Keywords: Energy strategies; Management of resources; Water, food and energy nexus; Renewable energy; Decision-making tools

1. Introduction

Often, political decisions are taken without the necessary coordination of different administrations and without considering the impact that a political decision in one activity may have on additional ones [1,2]. A deficiency in coordination arises between different branches at the same or different hierarchy levels in the public administration. Literature reflects clearly the fact that government tend to approach in an "isolated" way frequently results in policies that cannot be maintained at the current rate [3]. In this sense, there is a growing consensus about the importance

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Nomenclature

C→E	Cost per energy
CF	Conceptual framework
CI	Cost index
CO_2	Carbon dioxide
E	Energy
EB	Energy balances
E→E	Emissions for energy
ED	Energy demand
EP	Entry point, input
ES	Energy sector
FE	Food and energy
GHG	Greenhouse gas emissions
GIS	Geographic information systems
L→E	Earth for energy
LI	Land index
NS	Nexus sectors
NT	Water, energy, food nexus tools
P&DI	Policy and data input
p.u.	Per unit
RENS	Reference energy system
W→E	Water for energy
W→F	Water for food
WEF	Water, energy and food
WI	Water index
WLES	Water, land and energy systems

of the water, energy, and food security nexus and the need to devise and implement policies and actions in an integrated manner [4].

Integrated resource management can be defined as "the coordinated development and management of water, land, and related resources to maximize economic and social well-being in an equitable manner without compromising sustainability", and it has been so-called in recent times as "integrated water resource management" [5]. The first United Nations Water Conference, held in Mar del Plata, Argentina (1977), recommended greater attention to an integrated resources management, emphasizing that water plans should not only consider economic aspects but also ensure the optimal social benefit of water resources, as well as environmental protection [6]. The concept, popularized by the Dublin Declaration on Water and Sustainable Development (1992), promotes an integrated vision for resource management [5]. It stated that the management of water resources is an effective approach to address global challenges related to water management, restoration of degraded lands, adaptation to climate change, and the fight against hunger [7]. Some international bodies, such as OECD [8] or the World Bank [9] already recommend integrated resource management through these related methodologies.

The adoption of management based on the water, energy and food nexus requires a more appropriate perception of the associated benefits and exposure to danger for each of the nexus sectors, as well as an analysis of interactions between them in order to facilitate integrated planning and decision making [10]. In this sense, analytical frameworks are used to assess the impact of policies on different sectors [11] and inform policies by quantifying resource exchanges and providing an assessment through which the potential and unexpected risks associated with the nexus are identified [11–13].

After a deep review in the literature, it has been found that, even though some institutions and researchers, such as the FAO [14], World Bank [15], Pollit et al. [16] and Tol [17] have proposed some preliminary tools, they have been designed as frameworks for in-depth nexus analysis, not as simple, easy-to-use tools for conducting basic evaluations. These wide-ranging tools are intensive in terms of the information, time, capacities, and funding needed. To our knowledge, there is no tool available in the scientific literature that, having energy as an entry point (EP) or input and incorporating inputs relative to the specific explicit context, can be considered as simple. In order to address this gap, and as novel approach, apart from a deep review of existing models in the literature, this article presents a conceptual framework focused in the joint management of three fundamental resources: water, food and energy, but in this case, mainly focused on the energy as an EP related with the other resources, in a single of two ways relationship. This conceptual framework intends to be easy to apply but efficient at the same time.

The reminder of this paper is structured as follows. Section 1 states the objectives of the research article and provides an adequate background. Section 2 describes the review and selection criteria used to conduct the research. Section 3 proposes the conceptual framework for a tool that can conduct preliminary assessments of the basic impacts of the energy policy nexus. Finally, Section 4 explores the significance of the results and states the major outcomes.

2. Definition of frameworks to model nexus interactions

The frameworks used to model nexus interactions can be based on both quantitative and qualitative methods [18,19]. Although this paper focuses on quantitative tools, qualitative tools can also provide important information. The methodology used by the FAO to assess the nexus combines both tools [14]; while other institutions such as the United Nations Economic Commission for Europe (UNECE) together with the KTH Royal Institute of Technology use other methodologies that are mainly qualitative [20].

The modeling tools for nexus integration can assist decision making and identify local objectives that are in line with broader sustainable development objectives [21].

Although fully integrated planning is preferable, assessing water requirements against an energy strategy could provide very useful initial information for other water end-uses. Some of the available methods used, such as the one proposed by Food and Agriculture Organization [22] or the one proposed by Mohtar and Daher [23], adopt food as an EP; variants, such as the one proposed by the United Nations Economic Commission for Europe and Royal Institute of Technology [20], adopt hydric resources as an EP; additional tools, like [24], employ the power derived from the utilization of physical or chemical resources as an EP. This paper will, for the most part, be centered in an “energetic” view.

The intersectoral nature of the nexus indicates the importance of perceiving the intended meaning resulting from the interrelationships among water, energy, and food through scenario simulation [22]. In this sense, the development of scenarios from quantitative tools is adopted to explain a number of several and probable events that will or are likely to happen in the future [22]. In fact, these scenarios constitute reasonable gradual developments to the present circumstances which, according to the way the elements of the nexus evolve and interact, may serve to assess the implications of certain policy decisions [22]. For instance, some policies advantageous for the energy and food sectors might exert excessive stress on the hydrological plans of countries with drought problems by promoting excessive use of water due to affordable pumping. In order to address these risks, several analytical frameworks have been developed within the context of the water, energy, and food nexus [14,20,25,26].

The quantitative tools that analyze the impacts of energy policy on the nexus may vary in terms of their completeness, as shown in Fig. 1. The first block represents an “isolated” way of dealing with the situation, in which “political” and other data relevant to the energy sector (such as the resulting energy balance) are provided without considering the influence that it can have on the remaining elements of the nexus. Conversely, an alternate way of dealing with a larger content of scope (in the middle) would consist of a water, energy, food nexus tools with the essential facts serving as a receptacle for quantities relating to the energy sector but as too important data relating to water and food and land—in this case, providing outputs on the essential remaining nexus assets required for the policies.

Since the 2011 Bonn Conference [27], several frameworks have been developed and evolved [28–32]. The existence of different purposes has resulted in diverse boundaries for frameworks that have been developed at different levels — from a regional level [29,31] to a global level [33,34]. This variety of frames of reference with different inputs, outputs, and analytical characteristics has its origin in the complexity of the nexus [35]. The inputs are employed to characterize the schemes studied and their circumstances. With respect to the outputs, a set of tools focus only on one component of the nexus; other tools describe additional components, and the remaining

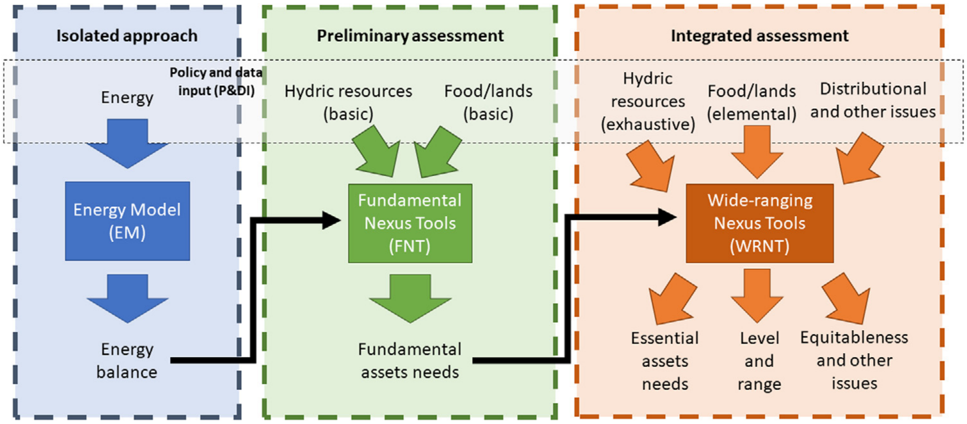

Fig. 1. Conceptual scheme of the modeling levels considering the water–energy–food nexus for energy policy. *Source:* Own elaboration.

ones show additional elements, such as available land area, minerals or GHG. Finally, the fundamental analytical characteristics of the tools may, in addition, be dissimilar. Although the kind of information necessary can change depending on the tools used, most of them depend on a large amount of data (inputs) that are often not available on a large scale [36]. This is because much of the data needed for nexus evaluations are not centrally located under the authority of a single agency and practices related to data management of different agencies often differ [35].

3. Review of integrated planning tools

The conducted review only includes tools that meet the following specific selection criteria:

(a) The tool deals with a minimum of two out of three essential features of the nexus.
(b) The tool permits to conduct evaluations at a wide-state level.
(c) The tool is, to a large degree, accessible and available for use or it is open access.

The examination principle by which tools are to be judged have been arranged into three groups—required inputs, proportionate outputs (and, as a result, replied queries), and analytical aspects. It should be noted that this research does not assess aspects such as in what way the tools can be employed to characterize scenarios and that an exhaustive analysis of the advantages and deficiencies of every tool is beyond its scope.

The specific review criteria are described below:

1. **Entry requirements**
   Main entries: these entries constitute the principal data in the examination, either with regard to facts and statistics collected for reference or analysis. These entries would, as a rule, have to be supplied by the user of the tool. Examples could be the amounts and types of energy available for the studied nation, the quality of being able to be used or distinct kinds of water being obtainable, access to land for cultivation, or the expenses associated to distinct energy or water technologies.
2. **Exits/inquiries replied to:** The standard of examination inside this category gives facts about what exits might be predicted from the tool and, as a consequence, what queries could possibly be answered with it.
   Policies on energy, water, or food and land use are not possible to be carried out separately from climate change for the reason that the impacts are clear and show two-way directions; each of the three nexus subdivisions produce and discharge a considerable amount of GHG and will be influenced by climate change. Even though considering the impact of climate change on the nexus' essential features is beyond the outlook of this research, a number of the revised tools consider the impacts of the policies evaluated or the schemes on GHG. A detailed nexus tool might allow the evaluation of the give-and-take that might happen among carbon dioxide emissions and the essential parts of the nexus.
   Because financial examination is essential to political decision-making, a number of tools are capable of supplying an assessment of the financial consequences of the schemes analyzed (in particular, the incurred

costs). The addition of non-financial expenses (i.e., consequences of an industrial or commercial activity which affects other stakeholders without this being reflected in market prices) might be important to consider the financial worth of ecosystem services (for example, maintaining areas with a large number of trees, land not used could lead to the capture of some of the CO_2 discharges and thus make the externalities connected with them smaller).

Moreover, some countries do not have a restriction on the surface of the land to be used, whereas other countries do so. A number of the revised tools are capable of supplying relevant information on the previously mentioned aspects.

3. **Analytical characteristics of the tools:** The standard of examination inside this arrangement describes a number of analytical characteristics of the tools that are treated as significant for this research such as its accessibility, allowed analysis or geographical restrictions application.

Built on the revised principles listed before, Tables A.1(a) and A.1(b) present an examination of the tools, showing the various principles included in the evaluated tools. Tables A.1(a) and A.1(b) have been outlined to supply an imaged explanation of the problems associated with each tool considering that if a criterion has not been assessed for a particular tool, the corresponding box within Tables A.1(a) and A.1(b) is left blank.

4. Conceptual framework definition

It has been proposed a frame of reference aiming to address some of the gaps previously identified—its main output being the assessment of the basic requirements of a given resource (such as the volumes of water in addition to land surfaces) combined by a number of particular actions for the power derived from the utilization of physical or chemical resources. The presented tool can (i) accommodate inputs that are particular to a given context; (ii) yield results in a useful and convenient layout; (iii) be uncomplicated from an analytical point of view, while also supplying a basic view of the situation.

The proposed conceptual framework is based on an approach based on situations in which the nation's energy balances (EB) are paramount for all the schemes. This allows the user to build a number of schemes by altering the EB connected to various energy policies (such as, for example, a higher adoption of inexhaustible energies) in addition to examining the rising effects on the water, energy, and food nexus. Despite the fact that this article focuses on renewables, the proposed tool deals with the full EB as, among other factors, a further development of inexhaustible resources would typically impact the remaining components of the nexus in consequence of the replacement of different kinds of energy that would otherwise be required.

In order to depict these replacements, it is necessary to consider the complete energy balance. The majority of nations collect the information of their EB as a division of their country-level data; while the International Energy Agency (IEA) does the same through a standardized structure for the processing, storage, and the display of data [37], which represents an essential benefit for the CF put forward.

The first step in using the proposed tool would be to provide an energy balance corresponding to a base scheme. Such an EB might depict either a current or a prospective energy scenario built on forecasts.

The next step would be to supply a substitute EB representing the energy policy scenario to be examined from the point of view of the nexus (e.g., by placing more attention on inexhaustible energies). Such an EB should reflect changes in the use of technologies and be consistent with energy policies that remain unchanged (the proposed tool estimates the accumulative EB simply by deducting the substitute and reference energy balances). The accumulative EB would depict the alterations in the energy circumstances as a result of the policy examined.

A following phase of the arranged tool would be to assess the implications of the incremental energy balance in terms of water, land, emissions, and cost. The tool would multiply the accumulative EB by the matrix data they describe. In this case, with regard to every kind of energy (energy balance vertical arrangements) and for each energy supply chain scenario (energy balance rows), it would result in (i) the quantity of water, (ii) land needed per unit of energy, (iii) the quantity of discharges expelled in each of these scenarios, or (iv) the unit expenses provoked. This way of proceeding is depicted in Fig. 2, in which every of the above-mentioned matrices has been named, correspondingly (i) W→E, (ii) L→E, (iii) E→E, and (iv) C→E. These data matrices are external data and are, generally, nation specific. The outcome of this phase is the elemental accumulative employment of water and land assets (such as capacity of water or earth surface), accumulative expenses or accumulative discharges originated by the energy policy examined.

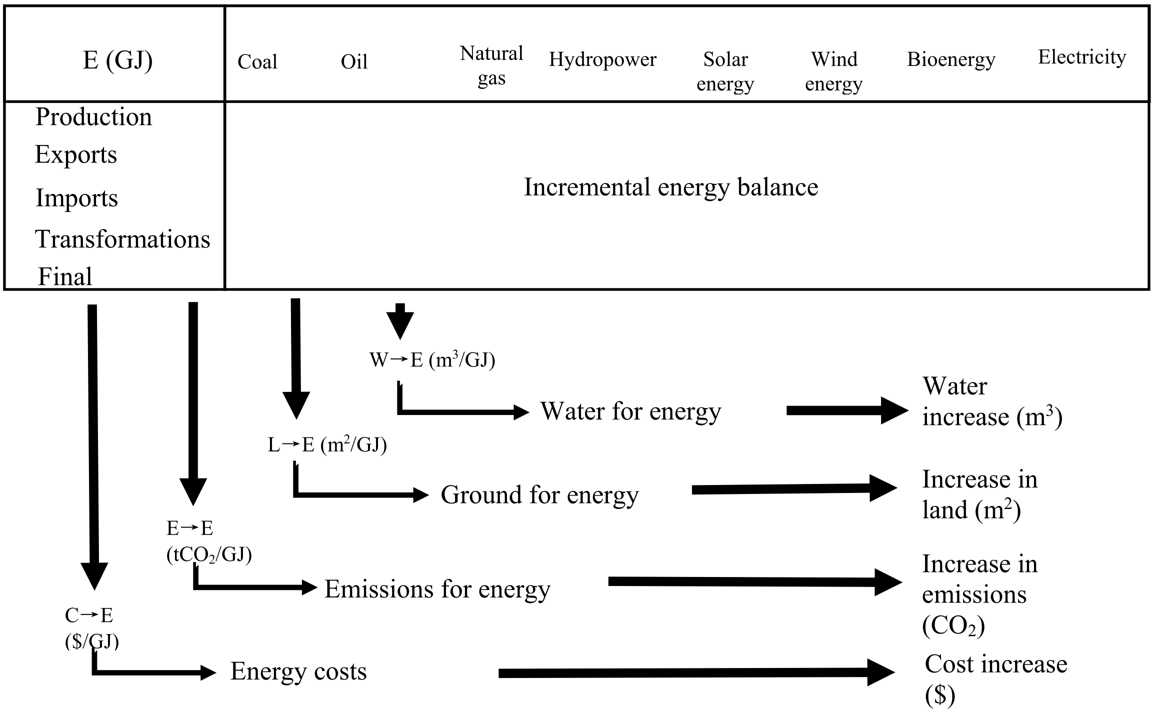

Fig. 2. Estimation of the implications of water, land, emissions and cost of the energy policy evaluated. *Source:* Own elaboration.

The proposed tool yields data around the meaning of the examined policy nexus, not about the way the policy should be planned to curtail those connotations of the nexus. On the other hand, and as mentioned before, this perspective exclusively supplies data around the essential resources needed, not the characteristics, allocation, or opposing employment of these resources (this would serve as a possible future improvement of the analysis).

The final step in the suggested CF would be to evaluate whether an accumulative employment of assets or discharges is tolerable. As discussed above, a given principle of action adopted may have the same performance in two different contexts but can be acceptable in only one of them [14].

As shown in Fig. 3, contrasting these tolerable levels with those of the EB available as another possibility (base scenario + accumulative) would generate four fragmentary indices (WI, LI, CI, and EI), each of which are indicated in p.u. values. In the case one or some of these indices show an index higher than the unit, it would signify that the satisfactory maximum has been surpassed. Lastly, the fourth fractional index shall be added to a general index according to the political significance that each feature has in the nation to be evaluated—in countries where a resource is considered critical, legislators may decide that its corresponding index is of greater importance.

The outputs resulting from the suggested CF might provide a basis for comprehensive qualitative and quantitative examinations. Although a particular number of qualitative features are satisfied by way of the data supplied by end-users in various phases of the suggested tool, comprehensive evaluation is necessary.

5. Conclusions

Today, most policy decisions with potential consequences for the water, energy, and food nexus are made through different institutions (such as distinct government departments or distinct positions in the public hierarchy of the government in power) without the necessary degree of coordination. The challenges facing the water, energy, and food nexus are, in part, a consequence of this "fragmented" policy applied to interrelated resources.

Access to data is a key challenge. In order to carry out a proper assessment of the water, energy, and food nexus, it is necessary to have access to both data from each of these sectors and data able to express the quantity of their mutual connections. The compilation of standardized data might serve to succeed in dealing with issues in

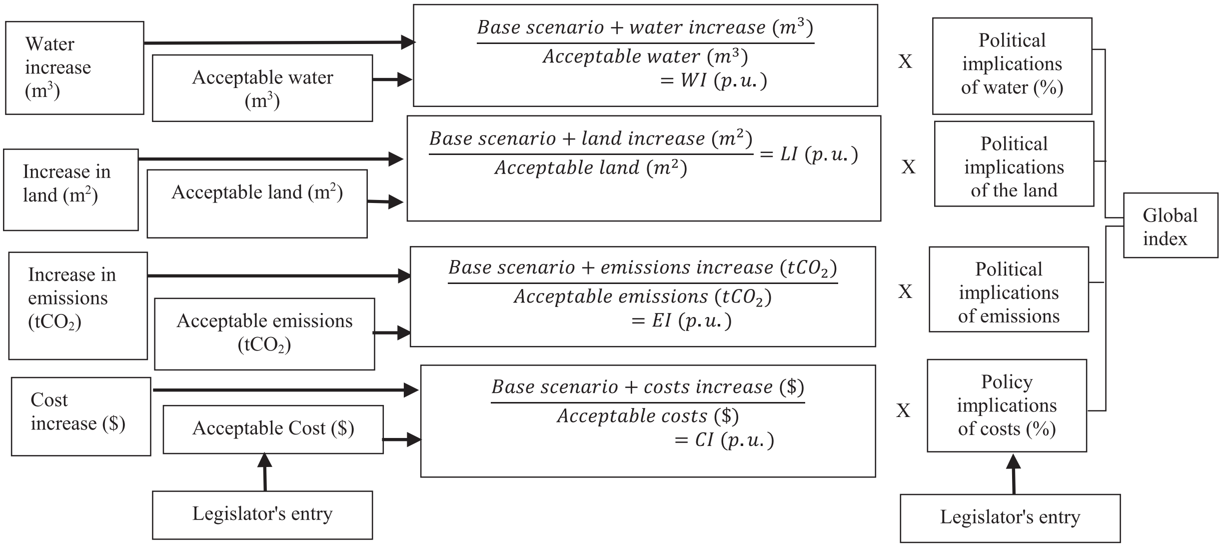

Fig. 3. Adoption of policy and data input to assess the water, land, emissions and cost likely consequences of the energy policy decisions examined for incorporation into a context-specific global index.
Source: Own elaboration.

existence at the current time related to consistency, comparability, and scale in addition to the absence of statistical information that are collected, observed, or recorded at regular time intervals.

- Most of the tools able to be used or obtained for people responsible for or involved in formulating policies nowadays are comprehensive and complex and require a significant amount of data, human resources, time, and economic sufficiency.
- Similarly, this research has identified the necessity for exploratory tools able to yield extremely useful basic estimations that could provide a basis for further (more complex) developments.

The reference frame put forward in this paper aims to propose an exploratory tool that has energy as an EP, which in turn provides a starting point that can ultimately support the integration of energy within the so-called nexus of water, energy, and food. The CF could present "snapshots" of the impact of renewable energy development (in addition to alternative approaches) on related resources such as water and land occupation.

For the proposed tool, every outcome constitutes a group of different energy policy decisions in which EB is accepted as key information. In this case, the tool put forward could roughly calculate or judge the value of the water, land, emissions, and cost involvements of every outcome in order to "combine" them into a global indicator that specifically regards the principle of actions proposed by the governments' choices for each particular circumstance.

The "product" presented by the tool put forward in this research might comprise an early step in the direction of a further exhaustive examination of the impact of the development of inexhaustible energies on the water, energy, and food nexus for several circumstances.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Table A.1(a). Review of evaluated nexus tools.
Source: Own elaboration.

Tool and reference	Standard of review					
	1.(a) Fundamental entries	2.(a) Energy	2.(b) Water	2.(c) Food	2.(d) Greenhouse discharges	2.(e) Economy
CLEWs [38]	Large amount of data required. Technical and economic parameters of thermal power plants, agricultural machinery, water supply chain, desalination terminals, fertilizer production, etc.	Energy balance, including electricity generation and refining Energy for food Foreign energy (virtual)	Water balance Water supply and desalination Water Pumping W→F W→F (hydroelectric power, generating station refrigeration, fuel derived immediately from living matter cultivated plants)	Irrigation Technologies Use of fertilizers Use of agricultural machinery	Restricted to both a particular area and foreign emissions Accumulated GHG discharges	Selected economic indicators
WEF 2.0: guiding integrative resource planning and decision-making (Daher & Mohtar, 2015) [39]	Local information and features of WLES Local production of WEF (by technology) Policy data taking into account particular circumstances	Consequences of food production on the commercialization of energy Energy used in water (pumping, treatment, desalination) Energy used for food (tillage, fertilizer production, distribution and harvesting)	Consequences of nutritious substances manufacturing on a restricted particular area	Degree of regional production of various kind of nutritious substances	Consequences of nutritious substances manufacturing on GHG discharges	Expenses of nutritious substances manufacturing
SEI (Stockholm Environment Institute) Modeling water & energy (LEAP/WEAP, 2014) [40]	Requires a large amount of data Techno-economic information on energy equipment	Comprehensive examination of ED and its transformations EB	Area or region drained by a river, river system, or other body of water devising Simulation of water requirements and provisions Water held underground in the soil or in pores and crevices in rock evaluation Water characteristics evaluation Storage and hydroelectricity evaluation	/	GHG discharges from the energy sector	Includes a financial module
Food and Agriculture Organization of the United Nations tool [16]	Evaluation of the country studied in order to classify it by typology	Specific to each type of intervention	Specific to each type of intervention	Specific to each type of intervention	/	Specific to each type of intervention

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Table A.1(a) (*continued*).

Tool and reference	Standard of review					
	1.(a) Fundamental entries	2.(a) Energy	2.(b) Water	2.(c) Food	2.(d) Greenhouse discharges	2.(e) Economy
WBCSD nexus tool [33]	Description of the distinctive nature or features of the energy sector Diagrammatic representations of areas of land based on GIS Characterization of the water needed for FE Data on the required workforce in addition to machine's availability	Energy needed for water Energy needed for food (for irrigation, fertilizer manufacturing or devices for performing work)	Water needed for power generation Water needed for food production	Food production	/	/
MuSIASEM (Giampietro et al. 2009) [41]	Requires a large amount of data Socio-economic indicators, including workforce evolution Land Availability Climate change impact assessment	Assessment of energy flows in society	Assessment of water flows in society	Assessment of food flows in society	Implications of all flows on emissions	Added costs and values
Diagnostic Tools for Investment (DTI) in water for agriculture and energy [42]	Complete set of data needed to characterize local supply of water to land or crops to help growth and hydroelectric power enterprises	Effect of hydroelectric power enterprises on bettering quality of life Percentage of people in a given area that have relatively simple, stable access to electricity	Water administration Use of water for (i) farming, including cultivation of the soil for the growing of crops and the rearing of animals to provide food, wool, and other products; and (ii) to the generation of power derived from the utilization of physical or chemical resources	Availability of food and individuals' accessibility to it, where accessibility includes affordability and agricultural manufacturing	Effect of supply of water to land or crops to help growth, typically by means of channels and hydroelectric power on GHG discharges	Agriculture's contribution to gross domestic product and profit production Expenditure requirements Effect of supply of water to land or crops to help growth enterprises on improving local quality of life
MARKAL/ TIMES (Loulou et al. 2005) [20,43–55]	Requires a large amount of data Techno-economic information on energy technologies Characterization of the RENS	Energy outlining with a large degree of technical specific aspects EB Effectiveness of energy policy	Water use in the energy sector	/	Emissions from the energy sector	Overall expenses of the ES, containing the necessary water provision

Appendix

See Tables A.1(a) and A.1(b).

Table A.1(b). Review of evaluated nexus tools.
Source: Own elaboration.

Tool and reference	Standard of review				
	2.(f) Earth	3.(a) Accessibility	3.(b) National geographical level	3.(c) Applicable to dissimilar geographies	3.(d) Uncomplicated although capable of providing a preliminary assessment, including explicit policy entries
CLEWs [38]	Biofuel crops Types of land according to the circumstances	It is possible that some developer works on the tool	National Global	It might be applied to dissimilar geographies. However, it is resource-intensive.	/
WEF 2.0: guiding integrative resource planning and decision-making (Daher & Mohtar, 2015) [39]	Land for food	It is conceivable that some developer works on the tool	National	Can be applied to dissimilar geographies	Simple reference frame Includes policies of importance for a sustainability index
SEI (Stockholm Environment Institute) Modeling water & energy (LEAP/WEAP, 2014) [40]	/	It is possible that some developer works on the tool Without charge for developing nations	National Global	Can be used to different geographies	/
Food and Agriculture Organization of the United Nations tool [16]	Specific to each type of intervention	It is possible that some developer works on the tool	National Subnational	Through the use of different typologies can be used in different geographies	A quick assessment of the nexus is uncomplicated and depends on the ready for use indexes. The adoption of nation categorization and the proposition indexes for every kind of intervention facilitates their use.
WBCSD nexus tool [33]	Land use	It is possible that some developer works on the tool	National Global Regional Local	Can be used to dissimilar geographies	/
MuSIASEM (Giampietro et al. 2009) [41]	Land use	It is possible that some developer works on the tool	National	It might be applied to dissimilar geographies. However, it is resource-intensive.	/
Diagnostic Tools for Investment (DTI) in water for agriculture and energy [42]	Cultivated land	It is possible that some developer works on the tool It might be used to dissimilar nations	National	It might be applied to dissimilar geographies. However, it is resource-intensive.	/
MARKAL/TIMES (Loulou et al. 2005) [20,43–55]	/	Applicable to any country	National Global Regional Local	It can be used to dissimilar geographies. However, it is resource-intensive.	/

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