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TOPICAL REVIEW

The climate, land, energy, and water systems (CLEWs) framework: a retrospective of activities and advances to 2019

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Abstract

Population growth, urbanization and economic development drive the use of resources. Securing access to essential services such as energy, water, and food, while achieving sustainable development, require that policy and planning processes follow an integrated approach. The 'Climate-, Land-, Energy- and Water-systems' (CLEWs) framework assists the exploration of interactions between (and within) CLEW systems via quantitative means. The approach was first introduced by the International Atomic Energy Agency to conduct an integrated systems analysis of a biofuel chain. The framework assists the exploration of interactions between (and within) CLEW systems via quantitative means. Its multi-institutional application to the case of Mauritius in 2012 initiated the deployment of the framework. A vast number of completed and ongoing applications of CLEWs span different spatial and temporal scales, discussing two or more resource interactions under different political contexts. Also, the studies vary in purpose. This shapes the methods that support CLEWs-type analyses. In this paper, we detail the main steps of the CLEWs framework in perspective to its application over the years. We summarise and compare key applications, both published in the scientific literature, as working papers and reports by international organizations. We discuss differences in terms of geographic scope, purpose, interactions represented, analytical approach and stakeholder involvement. In addition, we review other assessments, which contributed to the advancement of the CLEWs framework. The paper delivers recommendations for the future development of the framework, as well as keys to success in this type of evaluations.

List of abbreviations

CCT	City of Cape Town
CLEWs	Climate, Land, Energy and Water Systems
EGU	European Geosciences Union
FAO	Food and Agriculture Organisation of the United Nations
GAEZ	Global Agro-Ecological Zones
GLUCOSE	Global Least-cost User-friendly CLEWs Open-Source Exploratory model
IAEA	International Atomic Energy Agency
IAMs	Integrated Assessment Models
ICTP	International Centre for Theoretical Physics
IIASA	International Institute for Applied Systems Analysis
ISWEL	Integrated Solutions for Water, Energy, and Land
KTH	Royal Institute of Technology
LAC	Latin America and the Caribbean
LEAP	Low Emissions Analysis Platform
NDCs	Nationally Determined Contributions
NENA	Near East and North Africa
NWSAS	North-Western Saharan Aquifer System
NYC	New York City
OSeMOSYS	Open Source energy Modelling System
RRSS	Reference Resources to Services System
SDGs	Sustainable Development Goals
SEI	Stockholm Environment Institute
SFU	Simon Fraser University
TBNA	Transboundary Nexus Assessment
UNDESA	United Nations Department of Economic and Social Affairs
UN	United Nations
UNDP	United Nations Development Programme
UNECA	United Nations Economic Commission for Africa
UNECE	United Nations Economic Commission for Europe
UNIDO	United Nations Industrial Development Organisation
WEAP	Water Evaluation and Planning system
WEF	Water-Energy-Food

1. Introduction

CLEWs are closely linked. The analysis of the interactions and interdependencies between systems, particularly systems of natural resources and their use, is frequently referred to as 'nexus' assessment. This concept is not new, and nexus analyses have expanded over the past decade. In the late 2000s, the term 'nexus' was applied in the context of resources, such as land, water and energy [1–5]; or most commonly, to express the compromise between goals that simultaneously ensure water, energy and food security [6]. As they gained popularity, nexus analyses expanded to explore interactions across a variety of systems. The nexus of climate change, ecosystems and human health [7]; energy, minerals, society [8]; water, gender and health [9]; or climate change, land use and conflict [10] are examples of its broad application. Furthermore, the nexus approach supports the shift towards systems thinking across disciplinary fields, strengthening the importance of accounting for cross-system implications and dependencies. Such a change is a laborious task that requires overcoming the inter-institutional challenge of developing and implementing integrated planning approaches.

The majority of recently developed nexus approaches aim at investigating and analysing interactions between resource systems. Common examples include the FAO WEF approach [11], the WEF Nexus Tool [12], and the TBNA methodology [13, 14]. The CLEWs framework is another approach [15, 16]; that additionally focuses on the climate system. Climate is not considered a resource system, but a system that affects and is impacted by the resource systems of energy, water and land. Many of the nexus assessment approaches have been reviewed in the published literature within the past 5 years by [17–23]. However, no such review has been elaborated for the CLEWs framework. In parallel to the different frameworks and methods, a series of nexus-focused networks were created, such as the Food, Energy, Environment and Water Network [24], the NEXUS Platform [25], and the Nexus Project Cluster [26], to name a few. This paper does not aim to review nexus approaches or agendas. It fills the CLEWs literature review gap by providing a systemic analysis of the CLEWs framework. It starts by reviewing how it evolved throughout its different applications and, through this review, identifies potential improvements in the approach that can be applied both within the CLEWs framework and to other nexus analysis approaches.

The focus of the CLEWs framework is the analysis of interactions between the systems of climate, land, energy and water, supported by quantitative studies of interactions and use of resources. Thus, it is interdisciplinary in nature. These systems are defined at a biophysical level and comprise activities that predominantly make use of its resources. Sectors represent the activities that operate within a system, e.g. electricity sector is part of the energy system; water treatment and supply sector is part of the water system, while the food production sector is part of the land system. The CLEWs framework is not inherently system-biased, meaning that no system is given special focus through the basic design. The context and objective of each case study are what shapes the analysis and focus can be tailored as needed. This is done through the screening of systems and identification of systems' and cross-systems challenges.

Data intensity remains a challenge for quantitative modelling. Open datasets can assist when data is scarce or under the process of becoming accessible. The availability of data can define the scope of the assessment in terms of temporal scale if this is not defined *a priori*. For CLEW case studies, data intensity has not been minimized but streamlined through minimum data requirements for the representation of systems, and the identification of useful open databases for the characterization of systems and sectors. A short-term assessment will require more detailed data than a medium-term, where monthly or annual time series could suffice. Several CLEW applications investigate the dynamics between systems in the medium-term. This greatly relates to policy cycles, as sectoral plans typically span over 5 to 10 years. However, in studies where future climates are considered, the time span of the analysis is longer. Lastly, an integrated modelling framework using the oOSeMOSYS [27] is being used in capacity building activities by the UNDESA, the UNDP and UNECA [28, 29], and summer schools on modelling tools for sustainable development [30–34]. Efforts are ongoing to develop an open online course on the framework and its methods.

In terms of the modelling approach, IAEA (2009) suggests the development of formal approaches, which are general enough for the elaboration of national-level CLEWs assessments. These should build as much as possible from existing knowledge and expertise. In 2012, a multi-institutional team collaborated in the development of a cross-sectoral model exercise applied to the case study of the Island of Mauritius [15]. The authors developed an integrated modelling framework following a module-based approach. The analysis of the resource systems was carried out using three well-established modelling tools interacting as models: LEAP[14] [35], WEAP [36, 37] and GAEZ [38]. The soft-linking[15] of the models supported the investigation of cross-sectoral coherence of biofuel policy in Mauritius under different scenarios. Similarly to the IAEA vision, the authors [15] advocate for the use of existing knowledge, models and methodologies in the development of integrated assessments. Such an approach is associated to lower costs and resource requirements for model development and data gathering. Furthermore, it values existing expertise and promotes in-country advancement of knowledge. This can, in turn, enable the integration of the new knowledge in decision processes towards the achievement of sustainable development.

To provide a systematic review of the CLEWs framework, we first explore the similarities and differences in several CLEWs studies and outline other nexus-type studies that indirectly contributed to the advancement of the CLEWs framework. The paper is structured as follows. Section 2 clarifies the steps in a CLEWs framework in terms of methodological elements and the purpose of the assessments. In section 3, the review of its institutional background is described. Section 4 presents a summary and comparative analysis of CLEWs applications. Lastly, in section 5, we conclude with recommendations for the future development and wider dissemination of the CLEWs integrated approach.

2. The CLEWs framework

The development of the nexus approach, in line with its increasing number of applications, show a distinct trend over the years. In the late 2000s and early 2010s, the focus was on highlighting the importance of taking into account the interdependence of systems [6, 39–41]. Attention then shifted towards designing analytical methodologies to assess systems' interactions. Studies emerged exemplifying how to quantify the complex entanglement of systems [12, 13, 15, 42, 43]. More recently, and as the nexus approach establishes itself as a field of research and as a planning approach, the challenge has moved towards the incorporation into planning processes. Evidence of the impact of general integrated systems approaches (or proof of their influence) in policy design, and strategic planning are frequently asked for by practitioners. CLEWs framework applications share this goal of supporting policy and strategic planning. Among the existing CLEWs studies, the UNECE transboundary nexus applications stand out as successful examples of using nexus assessments to inform complex intersectoral policy dialogues [14, 44].

Examples of CLEWs applications exist under different spheres of action, not only in academia but also at national and sub-national policy levels with government participation. As the end goal is informing policy design and planning processes, the assessment of policies, or the elaboration of policy recommendations characterises most of the assessments. However, depending on the CLEWs challenges and/or the motivation of the analyses (e.g. decarbonisation, international cooperation on the management of resources), purposes can have different emphases. According to [39], CLEWs analyses were foreseen to support decision making, policy assessments, policy harmonisation and integration, technology assessments, and scenario development. In this paper, we update these aims in six types based on the review conducted. We identify six main types of purposes of CLEWs studies, especially in the assessment of:

- Policy (coherence and impact), by investigating the combined effect of different policies on the use of resources and their management (e.g. are there enough resources to attain multiple sectoral

[14] LEAP was formerly known as 'Long-range Energy Alternatives Planning system'.

[15] The process of soft-linking models consists of establishing links between two or more separate models by using the (direct or indirect) outputs of one model models on the other model(s). Such process requires the definition of a methodology for the soft-linking process as well as the harmonisation of common assumptions and input data [133, 134, 147].

and cross-sectoral goals), the feasibility of achieving multiple policy goals (e.g. national policies of different sectors) and the complex implications of cross-cutting strategies (e.g. NDCs, plans for SDGs implementation). In terms of policy coherence, to assess the potential implications of one sectoral policy across other systems in the CLEW nexus, to minimise trade-offs and establish compromises;
- Technology deployment and transition needed to achieve policy goals (e.g. renewable energy targets) or securing the availability of resources for different users via technological solutions within each sector or at the interface of sectors (e.g. reduced losses in water systems, improvement of agricultural practices, bio-energy, energy recovery from wastewater);
- Resource management and efficiency, by exploring options related to improving the efficiency in sectors using multiple resources or secondary products, and the transversal benefits of such measures (e.g. how improving water efficiency can reduce electricity requirements or energy efficiency at the household level can reduce water requirements in electricity generation);
- International cooperation and collaboration, supported by the qualitative analysis of nexus issues and model development. The shared use of resources and sectoral interdependencies are analysed to identify how win-win outcomes and multiple benefits could be attained while improving the overall efficiency of resource use;
- Climate studies to investigate the impacts of climate change over different systems and explore adaptation options and how mitigation can be achieved in an integrated system perspective. Integrated assessments can also inform on the climate resilience of systems and on ways of attaining decarbonisation;
- Other purposes. CLEWs assessments can meet other goals than the ones described above, while also exploring some of the above characteristics. Assessments can be conducted primarily for research purposes, without being related to a particular institutional application [45, 46]. Other aims include supporting the dissemination of the framework [42], or the establishment of communities of practice [47].

Since its first exemplification in 2009 [16], the CLEWs framework has evolved over the years. The activities in a CLEWs-type assessment can generally be organised in five broader phases, each of which encompasses specific methodological steps. These phases, which are summarised in table 1, are flexible and adaptable to the study being conducted. They consist of (a) profiling of systems; (b) pre-nexus analysis; (c) analytical approach; (d) analysis of results; and (e) reporting and recommendations. The context and purpose of the case study influence how the assessment is conducted and can vary or put different emphasis on the guiding phases presented. The involvement of stakeholders has also become a more regular practice in CLEWs assessments, from nexus dialogues to capacity building activities. Stakeholder involvement is linked to the aim and scope of the application. If assessments aim at informing planning processes, then the collaborative approach is required. Whereas, when assessments are academic exercises, participatory processes may not be required. In table 1, we indicate when and how stakeholders could be involved in the different phases of the assessment process. In continuation, we describe the main phases in the framework.

When carrying out a CLEWs assessment, analysts start by screening each of the CLEW systems in the case under study (phase 1). This phase consists of gathering understanding the characteristics of each system and how it functions (e.g. including development trends, policies, availability of resources). Although the intention is to move away from siloed perspectives, it is vital to understand the systems within their natural or organizational boundaries. This enables the identification of drivers and pressure points and the importance of interactions with other systems. At this stage, it is also crucial to identify foreseen trends, policies, and strategies that affect each system or its sectors.

The individual characterization of CLEWs systems (phase 1) is followed by the identification of their interactions, phase designated as 'pre-nexus assessment' (phase 2). In this phase, we distinguish two types of interactions: interlinkages, if the interactions are established between different systems; and intralinkages, if the interaction occurs within the same system. This mapping exercise is supported by the development of a RRSS diagram [45], where the interactions between resources, their transformation and use are made explicit. Examples of RRSS can be consulted in the supplementary information (available online at stacks.iop.org/ERL/16/033003/mmedia). The mapping of interactions allows assessing the dependence between systems and their sectors. The RRSS also functions as a guide for the analytical phase by informing on which interactions will have to be modelled or represented mathematically. This is also when the first assessment of data requirements and availability is performed.

The design of the analytical approach and its implementation (phase 3) follows. This phase is one of the most flexible components of the framework. Here, modelling tools and/or quantitative methods are selected, and the baseline cases are developed, often considering a 'business as usual' hypothetical future as a reference. If not enough data exists or can be accessed to conduct quantitative analysis, a qualitative approach can be followed instead. Opting for a more qualitative oriented approach may

Table 1. Main phases in the CLEWs framework and respective methods.

	Phase 1 CLEW systems' profiling	Phase 2 Pre-nexus assessment	Phase 3 Analytical approach	Phase 4 Analysis of results	Phase 5 Reporting and recommendations
Description	Screening of each CLEW system in terms of historical developments, status and foreseen trends, in addition to the review of sectoral policies and strategies. Study boundaries setting.	Identification of systems interactions, their dependencies and pressures, for the identification of CLEWs challenges.	Design of the analytical approach taking into account data availability, duration of the assessment, and methods and tools available to represent the systems and their interactions adequately. The analytical approach is both quantitative and qualitative.	Analysis of results and/or model refinement. Conduct additional model runs and iterations. Visualization of results and interpretation of results.	Reporting Summary of key findings in terms of trade-offs, synergies and opportunities. Recommendation of strategies and policy direction (in light of the development goals).
Methods and processes	Review of literature Review of Sectoral Policies Identification of sectoral trends and challenges	Evaluation of sectoral goals and identification of challenges. Comparison of policy goals Mapping interactions between systems and sectors. RRSS diagram Participatory workshops, questionnaires.	Mapping of interlinkages across sectors. Scenario planning and development. Quantitative Data preparation and processing (and management). Selection of modelling tools. Model development Other quantification applications and methods. Define the process for linking models and methods. Sensitivity analysis. Qualitative Inventory of solutions. Benefit analysis. Participatory workshops, questionnaires	Data management and results database. Preparation of results visualization. Selection and preparation of pool of indicators/reference metrics for scenario comparison. Summary of emerging trends, trade-offs and opportunities. Reassessment of the inventory of solutions.	Identification of solutions and/or policy. recommendations from the quantitative analysis. Elaboration of dissemination materials (i.e. reports, presentations, policy notes, scientific publications).
Stakeholder involvement[16] (optional)	Stakeholder mapping	Stakeholder engagement and consultation. Capacity building on the nexus (e.g. interactions between systems, identification of nexus issues).	Stakeholder consultation (e.g. data gathering, study assumptions, analytical approach, co-development of models). Capacity building in modelling tools for the investigation of nexus issues.	Stakeholder consultation of the findings of the analysis (which may result in the adjustments to the analytical approach).	Stakeholder collaboration in dissemination of study and integration in planning processes. Capacity building in tools and methods for CLEWs.

require fewer resources, and allow for the exploration of issues for which data may not exist or may not be possible to incorporate in the modelling analysis, e.g. value of ecosystems, rural development, social implications, and impact of forest degradation. The reference case includes the current policies in place as well as medium-term plans and strategies likely to be implemented. The calibration of the baseline case (scenario) confers robustness to the modelling work, reducing bias to the extent possible, and should

[16] The stakeholder involvement in CLEWs analyses is optional and dependent on the aim and scope of the study.

ideally seek validation from policymakers or other stakeholders involved in the assessment. This phase also includes the design and implementation of scenarios to study the CLEWs challenges identified in the previous phase of the framework and could result in the update of the interactions mapped and/or considered in the analysis.

The analysis of results from the analytical step is the next phase in the framework (phase 4). This phase can include consultation with stakeholders in the context of each case study. New iterations and/or scenario runs may be required if results are not conclusive or to test further the dynamics of specific interactions. Outputs and preliminary findings from the qualitative approach, if conducted, are also discussed with stakeholders.

In the last phase of the framework (phase 5), insights are distilled from the previous stages. Such ideas are often communicated in terms of trade-offs, opportunities, hotspots and synergies. Potential technical or governance solutions and related recommendations are standard additions to the process for informing decision-making and policy design.

The five overarching phases we described aim to provide methodological guidance in the development of integrated assessment of CLEW systems. They can be implemented in different geographic scopes and scales. The ordering of phases is indicative and certain activities could gain a transversal character if they are revisited and updated throughout an assessment. This is the case of the update of the analytical approach informed by feedback from case study stakeholders. Another example is the identification of relevant interactions between systems and their relation to the nexus challenge, which can be made obvious form the results of an integrated modelling exercise.

3. The institutional history of CLEWs

The CLEWs approach is applied broadly and by different types of actors and in different contexts. The strong institutional background of the CLEWs framework has enabled a recurrent connection to the policy domain [44, 48, 49]. In addition, the framework is constantly evolving due to the strong partnership between collaborating higher education institutions including with the KTH (Sweden) and SFU (Canada). In figure 1, we summarise selected milestones of the implementation of the CLEWs approach and its adoption in the work plan of different institutions. Next, we describe how various institutions have contributed to the development of the approach. We conclude this section outlining in figure 2 the expertise mobilised by the different collaborating institutions, described in the following sub-sections.

The CLEWs concept started in an institutional setting as an analysis of multiple-system dynamics between the resource systems [16]. The exercise was a first step in the conceptualization of a CLEWs analysis. This was done through the synthesis, in one single diagram, of the systems of climate, land, energy and water. The systems were then interconnected via main interactions, e.g. use of water in the energy sector for cooling and, use of energy for the operation of water systems, and use of land for cultivation of energy crops for the production of biofuels. In the conceptual exercise, each system is interpreted following a resources-to-systems approach. The IAEA highlights the need and importance of integrated CLEWs analysis for the elaboration of sound policies that can effectively contribute to the achievement of sustainable development. CLEWs capacity building and knowledge-sharing activities in the Member States are supported by the IAEA technical cooperation programme [50]. The programme supports the Member States in tackling socio-economic development challenges related to energy and the interactions with food, agriculture and water.

From 2011 to 2013 it developed into a multi-institutional and collaborative effort applied to the Island of Mauritius, coordinated by the IAEA. A number of institutions (FAO, IAEA, IIASA, SEI, UNDESA, UNIDO and KTH) contributed with their expertise in sectoral and systems modelling to an integrated exercise [51, 52]. IIASA and FAO used their land use methodology (GAEZ) to explore the potential to grow sugarcane depending on land productivity [38, 51]. SEI-US built a water model using WEAP to represent water supply and demand of the island. KTH focused on the development of the energy systems model in LEAP. This multi-institutional collaboration resulted in a journal article [15] and each institution also produced working papers detailing the approach and their contribution [51, 52].

3.1. Larger scale and transboundary studies

Up until 2012, little work existed in the assessment of the nexus in transboundary river basins. The research that existed focused on the nexus between water and energy [5]. The use of the nexus approach, combining the nexus dimensions of climate, water, food (agriculture), energy and ecosystems; was pioneered in transboundary basins by the UNECE through the work of the Convention on the Protection and Use of Transboundary Watercourses and International Lakes (Water Convention)[17]. This included the participatory nexus assessments of transboundary river basins and aquifers using a the TBNA methodology, a semi-quantitative methodology based on CLEWs [13]. The pilot case study was the Alazani/Ganykh river basin, in the Caucasus region, shared between Georgia and Azerbaijan. Three other river basins followed: the Sava River basin in South-Eastern Europe; the Syr

[17] The Water Convention is an institutional and legal framework for water cooperation, open to all UN member states. Its secretariat is hosted by the UNECE.

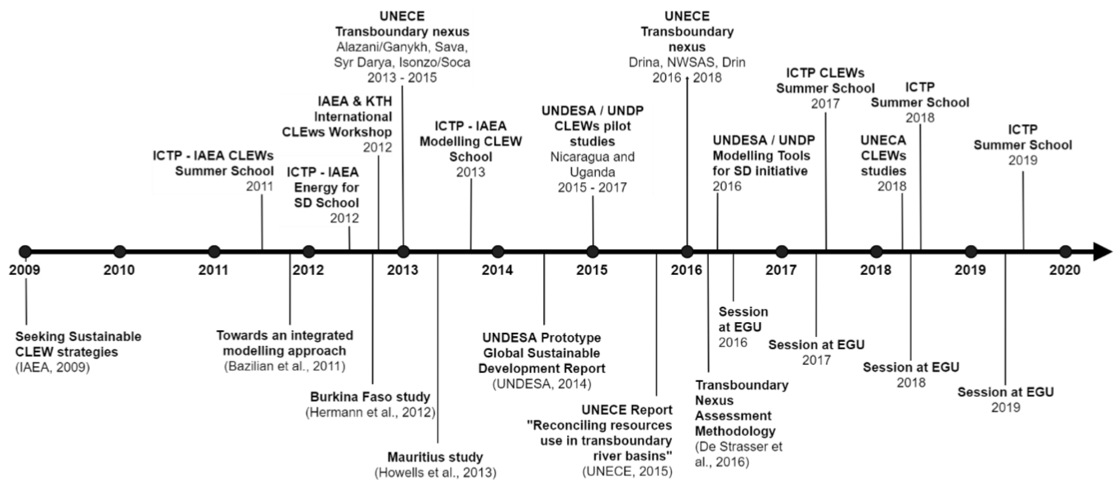


Figure 1. CLEWs timeline of selected institutional activities and initiatives in the period 2009–2019.

Darya in Central Asia; and the Isonzo/Soča, shared by Italy and Slovenia [14]. The work programme of 2016–2018 included the assessment of the Drina river basin, a tributary to the Sava River; and the NWSAS, located in northern Africa and shared by Tunisia, Libya and Algeria; and the scoping phase of the Drin River basin study, shared by Albania and Montenegro. Strong stakeholder engagement and participation, the governance analysis and the inclusion of the environment/ecosystems as a distinct dimension of the nexus are characteristic aspects of the TBNA methodology.

In 2013, the Division for Sustainable Development, part of the UNDESA, produced the prototype version of the Global Sustainable Development Reports [41]. This prototype report summarised the development trends and compiled success cases and practices in policy for sustainable development. Emphasis was given to the importance of scientific evidence in policymaking. As an illustration of global resource use trends, a chapter in the report was dedicated to the interdependences in development challenges related to the CLEW systems. The report also featured an example of integrated quantitative analysis, at the global level, of the use of energy resources, land, water and materials. The global model, GLUCOSE model, was developed in OSeMOSYS. GLUCOSE was developed with the additional purpose of research cooperation and replicability to smaller-scale contexts, e.g. regional and national; making use of open (publicly available) data.

3.2. Technical cooperation and capacity building

The year 2011 marks the year of the first CLEWs summer school at the ICTP, in Trieste, Italy. The one-week training event was co-organised by the ICTP and the IAEA. Course contents included methods for CLEWs assessments, an overview of modelling tools (e.g. MESSAGE, GAEZ, AquaCROP, and WEAP) suitable for the representation of resource systems and the analysis of systems' interactions. The training also included a reflection on the socio-economic implications of the CLEW challenges and analysis of case studies from a systems perspective. It emphasized the importance of an integrated approach for global development [34]. In the following year (2012), the CLEWs framework was included in another ICTP-IAEA summer school, under the topic of sustainable energy development. In this edition of the summer school, the CLEWs sessions focused on the Mauritius study [33]. Another CLEWs School in 2013 focused on discussing modelling advances of the CLEW interactions [53]. After a hiatus of 5 years, the ICTP hosted annual summer schools from 2017 to 2019 [30–32]. The 2017 edition was fully dedicated to the CLEWs framework and modelling CLEWs using one single modelling tool, OSeMOSYS [27]. The later editions focused more on the OSeMOSYS tool for energy systems analysis but included sessions dedicated to the representation and modelling CLEWs elements in an energy systems model.

In 2015, UNDESA and UNDP started to include in their capacity-building activities, the development of analytical capacity in CLEWs assessments. Nicaragua[18] and Uganda were the pilot countries for this initiative. The demand-driven capacity development program targets mainly officials from different governmental institutions. Since its start, the program has reached participants of over 20 countries. These country-level CLEWs assessments usually have a duration of 6–24 months and require strong collaboration with the national government. Frequently, three to four 1 week training events are

[18] After 2016, the CLEWs activities in Nicaragua were exclusively led by UNDESA.

organised in each country and support between training is provided remotely. In parallel to the CLEWS-related efforts, 2016 marks the year of the launch of the UN Modelling Tools for Sustainable Development website [54, 55]. The website showcases a series of modelling tools and country-projects. Additionally, it includes the materials for an outreach-training course on the various modelling tools [56].

3.3. Investigating climate policies and SDG implementation

The UNECA commissioned CLEWs work in two countries in 2018: Sierra Leone and Ethiopia. These studies assessed the land, energy and water nexus implications from the implementation of each countries' NDCs at the national level. The assessments, developed using OSeMOSYS, also served to highlight how open source tools could support the implementation of the Paris Agreement [57]. As per the request of the Ministry of Water, Irrigation, and Energy of Ethiopia, several UN agencies (UNDESA, UNDP and UNECA) have partnered in the development of a CLEWs assessment in Ethiopia [58]. The project aims at enhancing policy coherence for the achievement of the SDGs through CLEWs and at strengthening institutional coordination among implicated stakeholders.

3.4. CLEWs in academia and scientific research

In addition to the institutional work, the CLEWs framework has been published in the scientific literature, presented at numerous conferences. Since 2013, CLEWs has motivated several academic studies covering different spatial scales and contexts. Several peer-review publications were published over the years detailing CLEWs case studies. These are described in the following section of this paper. In addition, the CLEWs framework has been applied in multiple scholarly projects. These include larger-scale studies at the global level [59] and multi-country level in transboundary river basins [60–62], and the mixed-scale analysis of climate change impact on integrated resource systems [63]. At the national level, studies have focused on multiple development goals [64–73]; as well as with a particular focus on water resources [74–77]. Since 2016, KTH co-convenes regular sessions at the annual conference of EGU, along with the University of Cambridge, IIASA and other partners [78–81]. This event, which includes a session for oral presentations and posters, has featured over the years, several case studies that used the approach [45, 82–89]. Studies and CLEWs projects have also featured independently in academic conferences and meetings over the years [90–95]. The framework is part of the Nexus Project Cluster [26] and has informed the development of the Nexus Assessment Framework of the SIM4NEXUS[19] project, funded by the European Union Horizon 2020 programme [96].

International institutions have been instrumental in the promotion and implementation of the CLEWs framework. Its advancement has been supported by the collaboration with research institutions driven by expanding scientific knowledge. The impact and relevance of the approach have been assessed, framed and tested at the policy level by governments taking part in the initiatives. However, much is still do be done to consolidate the integrated systems approach in the planning process. In figure 2, we provide an overview of the different expertise drawn by different institutions to the development of the CLEWs framework and of its applications. Depending on the type of institution, its field of work, mission and practices, particular expertise can be directly or indirectly deployed during the planning and development of an integrated assessment. Collaborations can be forged upon the understanding of what type of contribution each institution can give. These synergistic collaborations will determine the success of the assessment [97].

4. Applications and key findings

The past decade has seen the development of several CLEWs-type analyses. Older applications were designed as integrated analysis exercises exploring context-specific challenges. Later, leveraged by institutional applications (e.g. UNDESA, UNECE) and knowledge advancement, studies gradually developed into higher-impact applications in planning and policy (e.g. governmental involvement, national development, and the Water Convention, in particular on transboundary cooperation).

In this section, we describe 23 historical and ongoing applications of the CLEWs framework and others that contributed to its development. These are summarised in table 2. Descriptions of each case can be found in the supplementary information material, including information used to conduct the quantitative comparison of interactions and a description of the phases of the assessment in relation to the CLEWs framework introduced in table 1. Applications are grouped by geographical scale, purpose, type of interactions analysed, analytical approach and extent of stakeholder involvement.

CLEWs studies have been used to highlight conflicts or lack of policy coherence at national levels. Fostering and promoting cooperation between countries sharing water resources and informing policy

[19] SIM4NEXUS, abbreviation for 'Sustainable Integrated Management FOR the NEXUS of water-land-food-energy-climate for a resource-efficient Europe', is a project funded by the European Union's Horizon 2020 research and innovation programme under grant agreement No. 689150.

Table 2. Overview of the CLEWs case studies reviewed in this paper.

Geogra-phical scope	Case study	Period of the study	Description	References
Local	CCT, South Africa	2015	Investigation of the energy implications of expanding water supply system to meet future demand; and effects on water demand of relocating agricultural activities to outside the city boundary for current agricultural land to be used for housing.	[98, 99]
	NYC, USA	2017	Urban-scale CLEWs study of NYC focused on water and energy-dependent urban service provision.	[45, 100]
	Oskarshamn, Sweden	2018	Cross-scale impact analysis of municipality-level decarbonisation path-ways on CLEW systems; and assessment of implications to SDGs.	[101]
National National (cont.)	Burkina Faso	2012	Investigation of CLEW nexus implica-tions of agriculture intensification and of the nation-wide use of jatropha as a biofuel.	[43]
	Mauritius I	2013	Investigation of climate impacts on elec-tricity generation, water supply and demand, sugar and bio-ethanol policies as well as on the transport sector. Map-ping of costs and benefits of various policy scenarios.	[15, 51, 52, 102]
	Mauritius II	2015–2016	Reconstruction of the Mauritius study in a single-model framework for train-ing activities and dissemination of the CLEWs approach. The model was used in the investigation of renewable and biofuel energy standards.	[42, 55, 103]
	Mauritius III[20]	2017	Development of a discrete optimization model for the CLEW nexus interactions using mixed-integer linear programming. The case of the Mauritius Island was used to develop and test the modelling approach.	[46]
	Nicaragua	2015–2019	Assessment of resource uses by differ-ent sectors (energy, water, agriculture). Development of modelling framework as a test-bed for sectoral policies and elaboration of sectoral outlooks taking into account the interactions between resource systems and the climate.	[73, 87]
	Uganda	2015–2019	To explore the ripple effects of one resource system policy on other inter-linked systems, such as the implement-ation of environmental flows on hydro-power generation for different climate futures, and the national irrigation plan, considering the national development plan.	[63, 104, 105]
	Sierra Leone	2018	Assessment of linkages and pressure points between energy, use of land and water systems using the CLEWs single-model framework, towards the achieve-ment of SDG7 (energy for all) and SDG2 (zero hunger).	[57]

(Continued)

Table 2. (Continued).

Geogra-phical scope	Case study	Period of the study	Description	References
	Ethiopia	2018	An application of the CLEWs single-model framework to investigate scenarios related to national energy policies, electricity access, climate change and penetration of biofuels in the transport sector to support the implementation of NDCs.	[57]
	Bolivia	2018–2019	The analysis investigates future changes in agriculture productivity for two hypothetical environmental development pathways focused on land-use change.	[106]
	Costa Rica	2019–2020	Investigation of decarbonisation policies in the sectors of water, land and energy.	[107]
Regional	Africa	2015	Water-energy study aimed at identifying electricity sector expansion plans considered robust across an ensemble of climate futures for four power pools in Sub-Saharan Africa.	[108, 109]
	Alazani/Ganykh	2013	Pilot case study that initiated the development of the TBNA methodology if the Alazani/Ganykh transboundary river basin in the Caucasus region, shared by Georgia and Azerbaijan.	[14, 110, 111]
	Sava	2014–2016	Assessment of the relevance of the Sava River basin water resources to the energy system of the South Eastern European countries sharing the basin, in terms of future water availability conditions and the added pressure of irrigation expansion downstream.	[14, 62, 111, 112]
	Syr Darya	2015–2017	Analysis of the implications of basin-wide electricity and water efficiency measures on the regional electricity system, expansion of RETs, and electricity trade re-establishment in the countries sharing the Syr Darya River basin, located in Central Asia.	[14, 111, 113, 114]
	Drina River Basin	2016–2017	Investigation of both the local aspects and national impacts of the management and use of transboundary water resources by the riparian countries of this sub-basin of the Sava. The quantitative analysis explored different configurations of reservoirs management along the basin.	[111, 115, 116]
	NWSAS	2017–2019	First application of the TBNA methodology to an aquifer system. The study aims to inform on agriculture viability and modernisation, water use rationalisation and reduction of aquifer depletion rate, and sustainable energy pathways to support water management and regional economic development.	[61, 111, 117, 118]

(Continued)

Table 2. (Continued).

Geogra-phical scope	Case study	Period of the study	Description	References
	FAO NENA Jordan	2018–2020	The study examines, with stakeholder involvement, the intersectoral challenges of water scarcity and droughts, agricultural productivity, water quality, and energy independence.	[119]
	FAO NENA Morocco	2018–2020	The study examines, with stakeholder participation, the intersectoral challenges of water scarcity and droughts, agricultural productivity, water quality, and energy independence in the Souss-Massa basin in Morocco.	[120, 121]
	LAC	2019	Investigation of possible futures of water security in the LAC region with identification of existing CLEWs nexus vulnerabilities, and assessment of water infrastructure needs for addressing related challenges.	[122]
Global	GLUCOSE	2013, 2014, 2019	Modelling framework for the identification of trade-offs and synergies between sectors in CLEWs and material industry at the global scale.	[47, 59, 123]

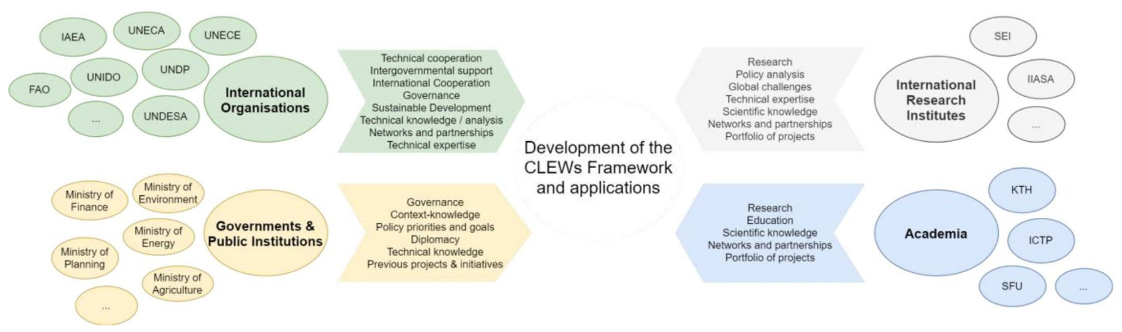


Figure 2. Mapping of the expertise mobilized by partners for the development of the CLEWs framework and of its implementation.

design by testing sectoral policies in an integrated analysis are some highlights of a CLEWs assessment. In parallel, these studies also build knowledge on the importance of integrated resource management and planning to governments and high-level policymakers.

A challenge in documenting case studies is that many times their analyses and findings are not published in scientific journals, but as grey literature (e.g. executive and technical reports, policy briefs). While academic publications benefit from peer-review, project-based studies can more tangibly reach stakeholders. There is a challenge in reconciling both academic and project research in a way that serves the needs of different types of audiences. Such an effort could contribute considerably to the convergence of policy-relevant insights and research findings towards a more effective bridging of scientific and policy processes. Although this work is beyond the scope of this paper, we contribute to reducing the gap between policy and science by clarifying key concepts, purposes and approaches in the integrated resource assessments in line with the CLEWs framework.

[20] The study of Mauritius by [46], although reviewed, is not included in the comparison of cases due to insufficient information available on the elements selected for the comparative analysis.

4.1. Geographical scope

National and regional studies constitute over 80% of the CLEWs (and related) analyses reviewed in this paper. A summary of the distribution of studies according to the geographical scope is shown in figure 3. International organisations are the leading promoter of this type of assessments among the Member States through the engagement of relevant national institutions. This fact relates significantly to how the approach started, the experience developed, and to the establishment of networks of practice. Previous studies play an essential role as dissemination-vehicles for the CLEWs approach. Dissemination is vital for the engagement of stakeholders who look for more practical examples of a complex (and ambitious) planning approach. Thus, national studies promote the development of new national studies, and the same relation verifies with regional cases. Studies over time tend to build on previous experience and knowledge, as the science of the nexus advances and expertise is created in the assessment of particular interactions. Local-level studies are data-intensive and require capturing, in more detail, the interactions between systems [45, 98]. This is in line with the fact that local levels are the ones dealing with implementation, which requires a solid and detailed understanding of systems. At this level, decentralised local competences and knowledge can be involved and organised to address local challenges and trade-offs. Global-scale studies require a certain level of aggregation to provide a high level of insights at a less granular level, which may reduce their relevance at national or sub-national geographical scales [47].

However, the advancement of computational capacity and automation of mathematical routines have contributed significantly to the improvement of such representations. Established IAMs, such as GCAM[21] and IMAGE[22] (e.g.), continue expanding systems' representation and their spatial resolution. Standing on extremes of the scale of assessments can limit the deployment of such type of assessments, at least, in a comparable format and with similar impact-level as national and regional studies. Collaboration between academia and international organisations is critical for the dissemination and advancement of the CLEWs approach. Such collaboration supports the realization of successful science–policy interfaces. Academia can disseminate in academic channels (i.e. journal publications, theses, conferences) and contribute to knowledge advancement. On the other hand; international and intergovernmental organisations can disseminate in their circles (regional meetings, task forces, institutional publications, etc) to facilitate the incorporation of such studies and their consideration to policy-making.

[21] GCAM stands for 'Global Change Assessment Model' and is an Integrated Assessment Model (IAM) primarily developed by the Joint Global Change Research Institute. The global model includes the representation of the systems of water, agriculture and land use, the economy and climate. GCAM is an open source software available at: www.globalchange.umd.edu/gcam/.

[22] IMAGE is an Integrated Assessment Model at global scale that focuses on the interactions between the biosphere and the climate system, developed by The Netherlands Environmental Assessment Agency (PBL). More information available at: https://models.pbl.nl/image/index.php/Welcome_to_IMAGE_3.0_Documentation.

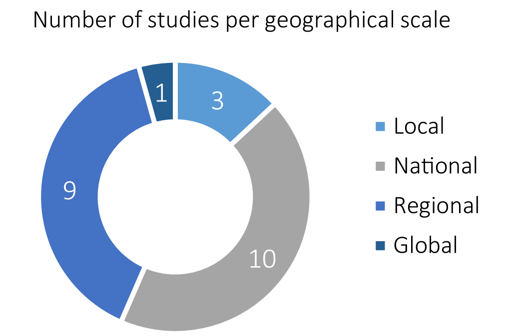


Figure 3. The number of studies reviewed per geographic scale. We revised a total of 23 studies, 22 of which were considered for the comparative analysis.

From small-scale studies, we learn the processes that could be essential to be considered at greater geographical scale assessments. For example, in the Cape Town case study, it is mentioned that treatment of wastewater is responsible for 67% of the energy use of Cape Town's water and sanitation services. However, wastewater treatment does not seem to be considered in other larger-scale studies. In the case of countries or regions with limited water treatment infrastructure, such processes could represent higher energy demand from the water sector, which would be necessary to consider in line with the development of the water and sanitation systems of the countries. From a top-down approach (larger to smaller scales), large-scale studies can uncover and flag critically relevant tipping points, e.g. the total level of emissions, use of fossil fuel resources, constraints affecting food, energy and water services. Whereas, small-scale assessments could account for them, if relevant, in their evaluations to mitigate their impacts, assess adaptation measures, or to decrease their compounding contribution.

In summary, knowledge and practice derived from different geographic scale assessments can benefit one another. Drawing learnings from studies across scales can facilitate the identification of challenges (from local, regional and global) and inform the development of the analytical approach and scenarios to be investigated. Additionally, such transfer could also contribute to improving information systems in a way that could facilitate data scaling and harmonisation.

4.2. Purposes of the CLEWs assessments

We reviewed the aims of different studies and classified them into six main types: policy assessment, technological deployment and transition, resource management and efficiency, international cooperation, climate studies, and others. In the last category, we consider aims that do not fall within any of the other five categories. Such purposes can vary from community development, dissemination of practices, state-of-the-art review, or purely research-oriented.

The distribution of purposes of the CLEWs studies across different geographical scopes is presented in figure 4. We note that all studies are multi-purpose, meaning that more than one purpose was identified per study.

More than half of the CLEWs studies, across all geographical scopes, aim to investigate resource-efficient pathways. In national-level cases, resource efficiency investigation is coupled with the analysis of the implications of sectoral policies across the nexus systems and the achievement of climate goals (e.g. emission reduction) or climate resilience. In the case of regional studies, resource efficiency is often linked to international cooperation and technological transition. Focusing on the sustainable management of resources, coupled with other purposes, often leads to the identification of trade-offs between sectors and natural systems (e.g. expansion of irrigation for water-intensive crops could lead to unsustainable exploitation of aquifers in Nicaragua) and synergies (e.g. water-saving measures can reduce energy use at household level in NYC). This strengthens the importance of integrated planning of resources. Policy and resource management are concertedly related, as the use of resources is typically regulated or influenced by sectoral policies and plans (e.g. irrigation, power sector expansion, water access, use of land). Technological changes are often the means to achieve specific goals. This includes the deployment of off-grid solutions for electricity access and water pumping in remote locations; deployment of carbon capture and storage technologies for decarbonisation, among others. Even though few case studies reviewed focused explicitly on the assessment of SDG interactions (i.e. Oskarshamn municipality), or on the achievement of SDGs (i.e. Ethiopia), all analyses can contribute to inform the planning for SDGs achievement. In the supplementary material (Excel file), we present an overview of the SDGs and targets that could be informed by each CLEWs-type analysis conducted[23]. We note that some of the case studies were developed before (or at early stages of) the formulation and adoption of the 2030 Agenda (e.g. CCT, NYC, Mauritius, Burkina Faso, GLUCOSE, Alazani/Ganykh, Sava). Higher coverage of SDGs would be foreseen if the studies had a focus on the Agenda 2030.

In terms of the relationship between purposes and geographic scopes, we find regional assessments to be markedly motivated by international cooperation. This characteristic stems from contexts of shared resources. Some of the regional CLEWs studies deal with transboundary watercourses, such as the UNECE assessments and the World Bank study [108]; or have regional development as a motivation for the assessment, such as the Morocco and Jordan cases. In the latter, findings are foreseen to be of relevance to the NENA region with similar nexus challenges. Below national level scales, studies tend to focus on local and national priorities and not so much of exploring regional dynamics of resources use. However, local nexus assessments can reveal nexus implications at wider geographical scales [101].

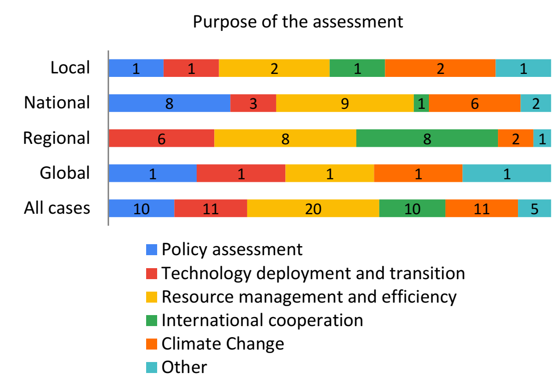


Figure 4. Overview of the purpose of the studies reviewed according to the geographical scope. We note that studies are multiple-purposes; thus, the number of studies per geographical scope does not coincide with the total number of purposes assigned to that geographic category.

CLEWs-type assessments are generally multi-purpose, with the aims ranging from two to five of the purpose-categories. Resource management and efficiency is the most common purpose, identified in over 90% of the studies reviewed. This supports the interest of understanding how systems can be managed with an integrated approach. On average, the studies focus on two to three purposes. The most frequent pairings are policy assessment and resource efficiency in national-level studies, and resource efficiency and international cooperation in regional studies. Purpose-triads are found at all geographical levels, supporting the multi-purposefulness character of integrated assessments.

4.3. Representation of interactions

Initial CLEWs analyses tended to focus on the energy sector, and often specifically on bioenergy use and electricity systems pathways. Consideration for the implications to other systems of water, land and climate was made, but with lesser detail. Such approach stemmed from the expertise of the teams working on the projects and on the effort to add a multidisciplinary dimension to the assessments. The Mauritius study, one of earlier examples of the CLEWs framework being applied, deviates from this approach, as

[23] The correspondence exercise showed that the majority of the cases reviewed (19 out of 22) could inform targets of the SDGs 6 (clean water and sanitation), 7 (affordable and clean energy), 12 (responsible production and consumption) and 17 (partnerships for the goals). Additionally, between 50%–85% of the cases (12–18 out of 22) could inform targets of the SDGs 2 (zero hunger), 4 (quality education), 13 (climate action), and 15 (life on land). The analysis also showed that case studies in their current design, were not able to directly inform targets of the SDGs 1 (no poverty), 5 (gender equality), 8 (decent work and economic growth), and 16 (peace, justice and strong institutions).

it was a multi-institutional effort that drew from expertise of different teams on the different CLEW systems. The engagement of multidisciplinary expertise is an important challenge and a requirement for unbiased and robust analyses. However, it should not be seen as a detriment to the development of CLEW analysis. Research groups and teams conducting multidisciplinary CLEWs-type analyses need, most of all, to understand the boundaries and limitations of the studies, and account for the need to develop knowledge in less familiar systems. In such cases, engagement of stakeholders is very important to identify the critical points of the system and assist in its representation.

An important characteristic of the CLEWs framework is that it is not biased towards any system when an assessment is initiated. As the analysis progresses, the focus of the studies tends to narrow on one or two systems. That is the case of the UNECE TBNA, where the nexus is analysed using a water-centric approach, as these are conducted under the scope of the Water Convention (but not only);[24] and the NENA region studies of Morocco and Jordan, where water productivity motivates the FAO-led effort. In figure 5, we illustrate the focus given to the different CLEW systems in the assessments reviewed. The graphic illustration results from ranking the focus level of each system, on each assessment, using a scale from 1 (less relevant) to 5 (highly relevant). The scores are determined considering the nexus issues of each case study and the systems assessed in the analytical phase of the assessment. Of equal importance is given to each CLEW system, then each system would represent 25% of each concentric line (as exemplified with the outer line in figure 5). The water and energy systems dominate the focus of the assessments; while land, followed by climate, are explored at lesser extends.

By examining the interlinkages represented, we can understand how the coverage of the CLEWs nexus was achieved. Interactions have been categorised in the literature in the context of the SDGs. The International Science Council [124, 125] classified SDGs interactions in terms of directionality, and on their dependencies in relation to context, governance, technology and time-frame. Also, in the context of the SDGs, McCollum *et al* [126] examine the literature for evidence of interactions between the SDGs and energy-related links. In the aforementioned study, interactions are classified in terms of synergies, trade-offs and linkages. In the context of the nexus of resource systems, Flammini *et al* [11] propose the elaboration of interlinkages matrices for the assessment of systems' linkages in terms of synergies and trade-offs. The matrices consider interactions between two of the WEF systems. This type of approach could assist the mapping of interactions identified in phase 2 of the CLEWs framework. Laspidou *et al* [127] make the distinction between direct and indirect interlinkages in the context of the nexus of water–energy–food–land–climate. Direct interlinkages correspond to unidirectional system-to-system interactions and are defined as first-order interlinkages. In contrast, indirect interlinkages correspond to interactions which propagate through different systems, involving more than two nexus dimensions (e.g. land–water–energy) [127]. In this study, interactions were classified in three ways: (a) in terms of the system of reference (i.e. of climate, land, water or energy); (b) in terms of systems involved (or directionality) (i.e. system-to-system interaction, e.g. climate → land); and, (c) in terms of their role in the representation of a system, using the categories: policy, process, natural systems, management and socioeconomics. The distribution of all identified interactions, according to the aforementioned categories, are shown in figures 6 and 7, respectively.

Additionally, although we compare system-to-system interlinkages, we acknowledge the dynamic nature of such interconnections and the propagative effects through them. However, since these can be multiple and specific to the context of each case, we decided to narrow down the overview of interactions. Thus, we consider interactions between different systems (interlinkages) that illustrate the effect of one system on another. In figures 7 and 8, we use the following notation to illustrate the type of interaction: system 1 → system 2, denotes interlinkage, with the symbol '→' symbolising impact, effect or influence on system 1 by system 2; and the symbols '↔' to express intralinkages occurring within the same system. To illustrate, we here give examples of interactions related to the land system:

- 'Climate → land': the precipitation that falls in a specific area of land, which will then influence a series of processes.
- 'Land → climate': the emissions of GHG from agricultural activities (residues left on the ground).
- 'Energy → land': the land used for energy infrastructure.
- 'Water → land', the water required for irrigation of croplands.
- 'Land ↔ land': the multiple uses of land from different sectors, such as energy, agriculture, and other infrastructure.

Intra-system interactions in the climate system are not represented nor assessed in since the models follow a steady-state representation. The climate system is not modelled within a CLEWs study, and climate inputs to the assessments are generally retrieved

[24] The TBNA methodology is not only water-centric and it expands the Integrated Water Resources Management approach to other important nexus dimensions of climate, food, energy, and ecosystems [13].

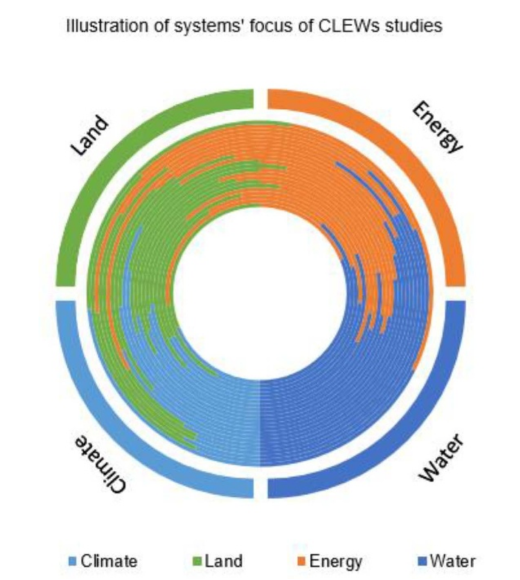


Figure 5. Coverage of the CLEW systems in the studies reviewed: (a) illustration of systems' focus of CLEWs studies.

from existing general circulation models (GCMs). For local and some of the national cases, emissions would probably not be significant to alter GCMs; however, they could be important to consider when regional climate models exist.

In figure 7, we show the distribution of unique[25] interactions represented in all assessments, in terms of directionality. We refer the reader to the supplementary information for the complete list of interactions and interactions per case study. Close to 80 unique interactions were represented in the assessments, with an average of 20 per system. Results show the number of interactions between and within CLEW systems is not equally distributed. Important to understand in CLEWs-type analyses is the representation of systems, their boundaries and possible limitations to the study. The representation and assessment of interactions depend on many factors. They may vary, for example, with the scope of the analysis, the nexus challenges understudy, the type of analytical approach followed data availability and accessibility, and on the modelling tools used for the quantitative analysis. Figures 6 and 7 provide an overview of the unique interactions considered in all studies reviewed. They show that interactions within the water and land systems are more commonly considered, followed by the systems of energy and climate. The distribution of unique interactions per interaction type is in line with the systems' focus of the studies, shown in figure 5.

The distribution of unique interactions by type (i.e. W → E, W → C, etc) per geographic scope is presented in figure 8. The figure informs not only

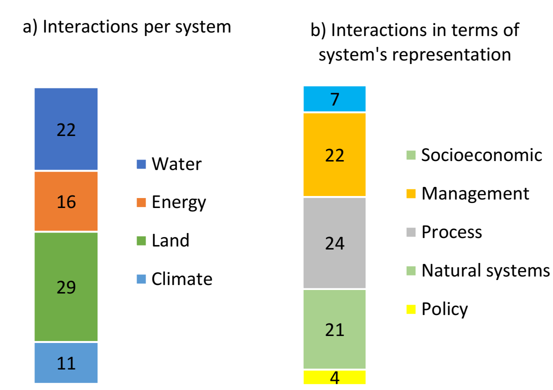


Figure 6. Distribution of CLEW interactions represented in the case studies in terms of: (a) system; and (b) role in the representation of systems.[26]

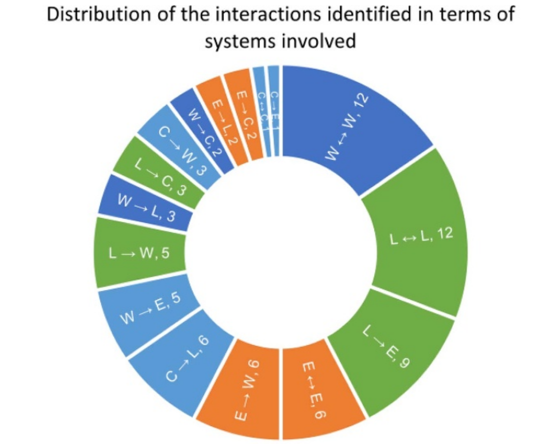


Figure 7. Coverage of the CLEW systems in the studies reviewed in terms of unique system-to-system interactions represented in the reviewed assessments. The symbol '→' denotes impact, effect or influence of one system on another; and '↔' represents interactions occurring within the same system. Interactions part of the climate system using light blue colour; land system interactions are shown in green; energy system in orange, and water system in darker blue.

about the most interactions types represented but also allows for examining if the representation of certain interactions types is more or less common under particular geographical scopes. Results indicate that national-level studies cover more interaction types (all 16) than the other geographical scopes. It is also at this scale that the highest number of interactions are

[25] By 'unique' interactions we mean interactions which are singular, or different, and thus are not doubled counted when considering all applications reviewed.

[26] Note: Natural systems' interactions refer to interactions related to biophysical processes. Socioeconomic, management and process interactions can be understood as anthropogenic interactions. They are considered here separately to identify their role in the analyses better. Process-type interactions refer to technological processes; whereas management interactions depend on how sectors operate (which can involve the operation of several types of technologies) and on decisions made regarding their functioning. Lastly, socioeconomic interactions are higher-level interactions that can influence both management decisions and/or artificial (technological) processes. Management and socioeconomic interactions implicitly embed social perspective in the analyses.

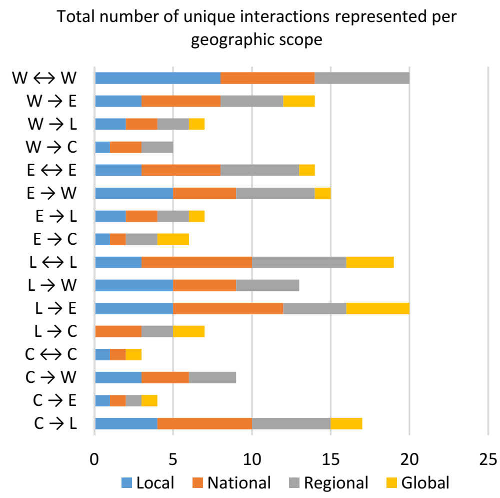


Figure 8. Distribution of unique interactions per type by geographical scope.

considered. An average of five interactions is analysed per system.

The importance of specific interactions may not be comparable across scales. It depends on the scalability of the issues and if they interfere with higher-level dynamics. It also depends on the characteristics of the local study, i.e. population density, access to services, consumer behaviour, and economic development, among others. Additionally, the natural systems features in each case study (i.e. resource availability (water, energy), food production, import dependence, etc) play a significant role. The transferability of methods between studies of different geographical scopes is one challenge of integrated assessments [17]. Studies tend to be very context-specific hampering the transferability of the approach, the lessons learnt, and the solutions identified. In contrast, regional and global assessments indicate that the geographical scope may limit the number of interactions represented, due to the level of aggregation required.

The least featured interlinkages types correspond to climate → energy, energy → climate, and energy → land. The top three correspond to land → energy, energy → water, and climate → land. Intralinkages within the energy and the water systems were also frequent, which can partly be explained by the expertise of the teams involved in the assessments. The total number of interactions represented across the studies vary significantly less in the case of national-level assessments, as it is seen in figure 10. The variation can be explained by the focus of the studies (water–energy; water productivity in arid regions, etc), their nexus context (the degree of dependence between systems), and the analytical approach followed. Several other factors influence the harmonisation of the representation of CLEW systems and their interactions across scales. Different CLEWs-type analyses are hence difficult to analyse at comparable levels of detail due to varying timeframes of projects, availability and access to data, the size of and breadth of expertise within the research team, the quantitative methods available, and the engagement with local actors (stakeholders), to mention a few.

Mapping interactions between CLEWs systems is an essential step of phases 2 and 3 of the CLEWs framework, described in section 2. Such exercise is key for the understanding of nexus challenges, their causes and how they are affected by or impact other systems. It also provides for a diagnostic overview of interactions, which may be sensitive to sectoral policies or resource management aspects. In terms of stakeholder involvement, interlinkages mapping can stimulate their engagement and active involvement, both in terms of the identification of critical interactions as well as to facilitate communication within a transdisciplinary context. Interactions investigated are more refined in smaller geographical scale contexts, in opposition to larger-scale assessments that require a higher level of aggregation in the analysis.

represented, explicit in figure 8. In the local, national and regional studies, about 30% of the interactions are intra-systems when compared to the largest geographical scope, where these represent (on average) one-fifth of the total number of unique interactions described. Smaller geographical scope assessments require more detail in the representation of systems, thus focus on less number of interlinkages and consider a higher share of intralinkages (figure 9).

Local-level studies show an average number of 12 unique interactions represented per system. Interactions between the water and land systems dominate, and more than 40% of the water interactions are intra-system. In terms of interlinkages, the average is seven.

The national studies show the highest number of unique interactions and more balanced spread across systems (see figure 10) if we account for some of the interactions in the land systems being related to the water cycle. Close to 70% of the interactions correspond to interlinkages. Water and land are the systems which contain most intralinkages.

Regional studies show a similar trend to the national geographic scope in terms of the number of unique interactions assessed. On average, the representation of interactions across systems is relatively balanced; however, the distribution differs considerably between regional studies, as illustrated in figure 10. More recent studies represent a higher number of interactions (e.g. LAC, FAO Morocco and FAO Jordan). Also important to note is that the FAO study has a national focus but regional significance. Climate and Energy are the systems with the highest number of interlinkages represented. On average, about one-fifth of the interactions are intra-system.

The global scale (represented by one case study) is the geographical scope with the least number of interactions, which relates to the level of aggregation

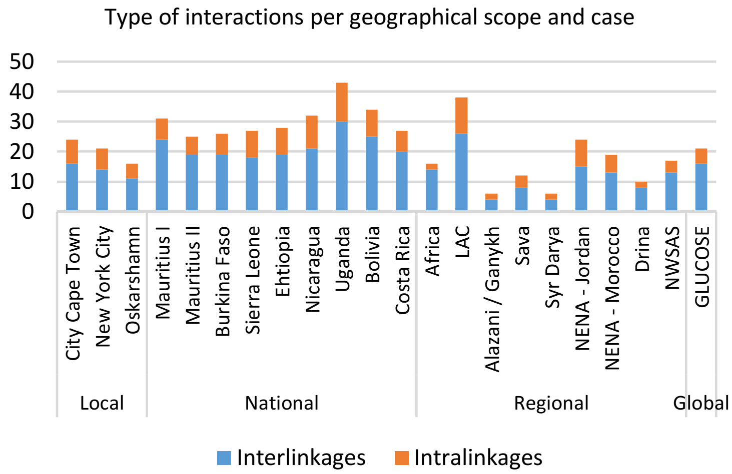


Figure 9. Distribution of type of interactions (inter- and intra-linkages) per case study.

However, interactions can be explored in levels, from more generic to specific. Such an understanding can be obtained by comparing the interactions examined and represented in integrated assessments, such as the ones we review in this paper. Other than interactions between systems, we also find that the representation of interactions within the same system is also part of an integrated systems' analysis.

4.4. Analytical approach

An important element in a CLEWs-type study is the choice of an analytical approach, which can combine qualitative and quantitative methods. Examples of qualitative methods include the mapping of interactions (inter- and intra-linkages), the assessment of their relevance and identification of nexus challenges (frequently through participatory processes). These are always included in national and regional studies. Within the quantitative approaches, we find different use of modelling tools. Their selection can be influenced by several factors. Some relate to the project design, for example, the timeframe of the investigation, size of the analytical team, expertise in the nexus issues under investigation, the existence of modelling frameworks and/or the need for the development of new methods. Others depend on external aspects, related to the case study context, such as data availability and accessibility, the expertise of the stakeholders in systems thinking, and the participation of stakeholders with modelling expertise, to list a few. When planning the analytical approach, the analyst(s) must adjust methods and methodologies to data available and accessible, consider the scale of the system-of-systems, the purpose of the analysis, and the nexus challenges at stake, to identify the level of detail required and relevant for the case study. This preparatory work is also essential for involvement and communication with stakeholders. Besides, analysts need to consider the capability of modelling frameworks to represent and investigate nexus challenges. A comprehensive compilation of methods and tools for nexus assessments was performed by [17], and a summary by the UNECE [128].

Moreover, modelling tools have limitations, which, coupled with the tool suitability to address nexus issues could undermine the development of an assessment. Uncertainty is another aspect to consider at the different levels of the analysis, in particular in systems with different temporal and spatial scales. The perception and understanding of a system by the experts conducting an assessment can also introduce uncertainty [129].

In the development of CLEW studies, we distinguish four main types of analytical approaches. These are listed in table 3. The first, 'type 0', refers to analyses which are dominated by qualitative methods. This is the case of the TBNA of the Alazani/Ganykh river basin, which was the pilot case in the development of the TBNA methodology [14]. The study focused on mapping the CLEW, food and ecosystems linkages with strong participation from stakeholders from the two riparian countries, Georgia and Azerbaijan. Nexus challenges were identified, and solutions were explored in terms of how impacts were translated across the different nexus systems. The remainder three approaches are dominantly quantitative and distinguished in terms of the modelling approach. 'Type 1'-studies apply CLEWs methods while focussing mainly on one system, although consideration is made for impacts and requirements to/from others. 'Type 2'-studies use a single modelling framework to represent the majority of the systems under analysis; and 'type 3'-studies incorporate soft-linking between system-specific modelling tools (e.g. an energy model coupled with a water systems model). This is the case, for example, of the linking of energy systems models, such as OSeMOSYS or LEAP, with water

Table 3. Types of analytical approaches in the reviewed studies.

Analytical approach	Description	Example of applications
Type 0	Qualitative	Alazani/Ganykh [14]
Type 1	Specific quantitative methods, accounting, simulation, a sectoral model with the accounting of implications to another system	NYC [45, 100], Burkina Faso [43], Oskarshamn [101], City of Cape Town [98]
Type 2	Full integration of CLEW systems in one modelling framework	GLUCOSE [41], CLEWs Mauritius [42, 103]
Type 3	Soft-linking of sectoral models Use of mixed-methods (e.g. geospatial analysis, modular programming, etc)	Mauritius [15]; Uganda [105]; Drina River Basin [115]; NWSAS [117]

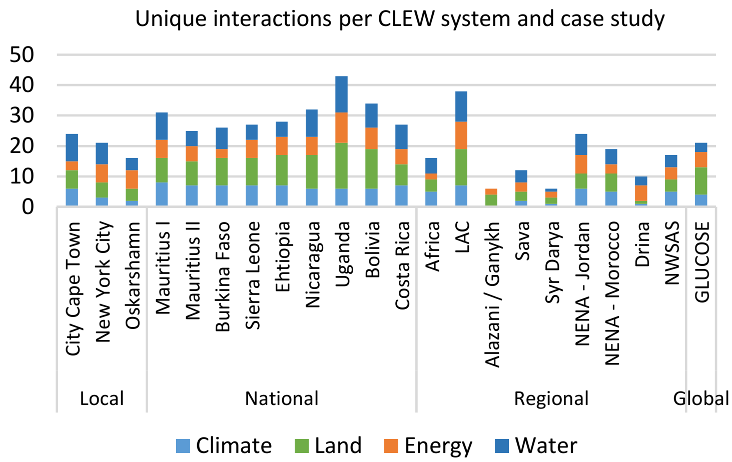


Figure 10. Unique interactions per CLEW system and case study.

systems models, such as WEAP,[27] in the Mauritius study Mauritius [15]; Uganda [105]; Nicaragua [87], and Bolivia [106].

The CLEWs framework is not prescriptive in terms of tools to use in an analysis of the analytical approach. Any modelling tool or framework can potentially be used in a CLEWs-type assessment as long as there is an understanding of how the tool (or set of tools) can examine the nexus challenges in question. In the description of cases reviewed in the supplementary material, information is provided regarding the tools and methods used in each case. Automatic soft-linking between specialised models (e.g. water, land use, energy, economy, climate, agricultural managements) is found in IAMs,[28] which have processes in place that enable the automatic link between different specific modules [130–132]. This is not always the case when tools typically used for sectoral analysis (which focus on one single system) are to be used in an integrated assessment. The process of linking tools that have not been linked before requires a comparison of modelling structures, assumptions, scales, inputs and outputs, and the identification of linking elements (which can be direct or require processing). In the supplementary material with the case studies descriptions, the diagram of soft-linking between LEAP, WEAP and GAEZ has been added to the description of the Mauritius case study to illustrate the model elements used in the linking process of the tools. Soft-linking models can be more practical than hard-linking, more transparent, enable new knowledge production in terms of tool integration [133], and allow for more complexity to be represented [134–136]. The previous characteristics can also be disadvantages if the linking process and iterations delay the analysis. However, nowadays, such linking routines can be established that allow for performing integrated model runs without much effort [136].

Figure 11 summarises the analytical approaches followed in the case studies, distributed by geographical scope. Single-model development (type 2) and soft-linking of sectoral models (type 3) are the most common. The total number of cases exceeds by three the total of studies (22) since two approaches were followed in the Oskarshamn (types 1 and 3), and Nicaragua and Uganda (types 2 and 3). The combination of sectoral models is more common in regional

[27] The link between WEAP and LEAP is possible directly through the WEAP interface, using the dedicated menu option [148, 149].

[28] For a list of IAMs part of the Integrated Assessment Modeling Consortium, and respective links to model documentation, see [150].

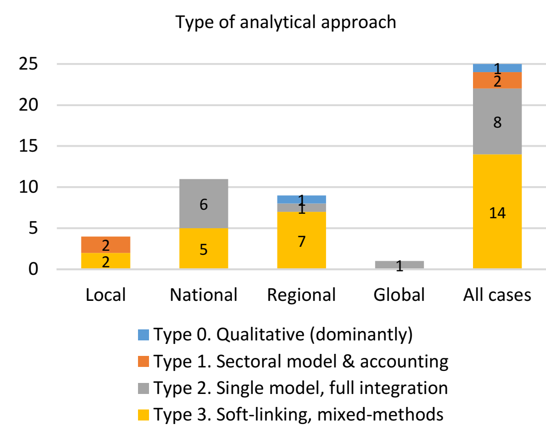


Figure 11. Overview of the analytical approach followed in the case studies by geographical scope.

assessments; while in national cases, the single-model approach dominates.

The analytical approach to be followed greatly depends on the characteristics of the cases, their purpose, and their background in terms of the initiative. Underlying these elements, we find multi-disciplinary teams of experts and stakeholders from a variety of fields of work, who mobilise their expertise to the assessment. It is vital that the teams conducting the assessment comprehend and are informed of the limitations of the tools and methods used, as well as of the uncertainties involved. Very importantly, they should understand the capacity of the analytical approach to inform on the nexus challenges under investigation.

4.5. Stakeholder involvement

A characteristic of many resource nexus analyses is stakeholder engagement and participation. Involving stakeholders in nexus analyses can have multiple benefits, as learned from experiences from other fields, such as environmental modelling, ecological risk assessments and water management, to name a few. Advantages include the discussion and establishment of a shared approach to a multi-sectoral issue, consensus-building among stakeholders and analysts [137]; transparency achieved by the engagement of several types of actors (policy, private sector, and civil society) [137]; uptake of the project and shared goals; collaboration in the identification of solutions [138]; better decision making [139]; improvement of modelling and quantitative tools [140]; and streamlining the implementation of solutions.

In the UNECE assessments, the stakeholder approaches include surveys, focus groups, nexus dialogues and task forces. In the UNDESA/UNDP approach, we find the involvement of stakeholders as focus groups, and in capacity building activities, which enable the co-development of the analysis and knowledge transfer with these stakeholders. Other nexus approaches also recognise the importance of stakeholder engagement in nexus assessments. This is the case of the Water–Energy–Food Nexus [12, 138], the ISWEL project in the Indus basin [141], the DAFNE[29] PIP procedure [142], and the assessment of climate, water, energy, food and land in the SIM4NEXUS Project [143].

In this section, we analyse the involvement of stakeholders in terms of their level of engagement, which is shown in figure 12. To do so, we considered three categories of involvement: (a) if there was no engagement; (b) if stakeholders were consulted, e.g. through interviews, participatory workshops, nexus dialogues, etc; and (c) as participation, if stakeholders, beyond engaging in consultation activities, also played a more participative role in the development of the assessment (e.g. model development, data mining and processing, scenario development and implementation). Stronger stakeholder engagement was verified for national and regional case studies, where we find in many cases stakeholder consultation coupled with participation. Six of the twenty-two case studies analysed did not exercise the involvement of stakeholders. The majority of the national and regional studies show evidence of stakeholder consultation and participation initiatives. In the case of regional studies, such an approach stems from the purpose of the assessment, which is greatly motivated by international cooperation. As for national studies, participation was linking to capacity building initiatives. Engaging and involving stakeholders has shown to support the dissemination of CLEWs research. Both in the UNECE and UNDESA/UNDP CLEWs initiatives, stakeholder engagement has led to new applications. Implicitly, stakeholder involvement, other than ensuring context-relevant assessments, also functions as a dissemination strategy among peers (policymakers and other decision-makers). Involved stakeholders realize that it is possible to contribute to scientific analysis and that their opinions and expert knowledge have a role to play in the assessment. However, there is a certain lag in the dissemination of studies outside the scope of application. It would benefit the community, and the framework, the production of outputs at a timelier pace and through a diversity of channels (e.g. scientific journals, institutional reports, institutional platforms online, policy briefs, popular science articles, etc), making use of the variety of agents involved in the study for broader dissemination of the work.

The involvement of stakeholders is present in the majority of the applications. However, although an approach with clear advantages, it needs to be carefully planned for the engagement to be meaningful and relevant to the assessment. Another aspect, not

[29] DAFNE, abbreviation for 'A Decision-Analytic Framework to explore the water-energy-food Nexus in complex and transboundary water resources systems of fast growing developing countries' is a European Union Horizon 2020 funded project under Grant Agreement No. 690268.

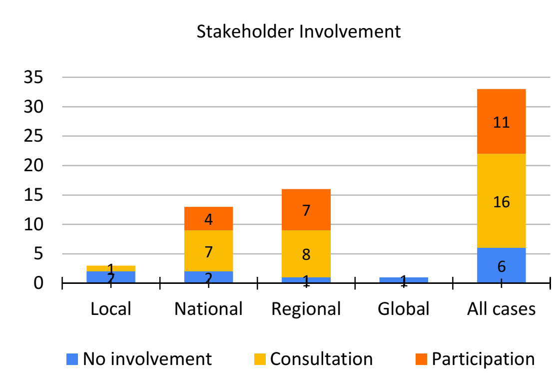


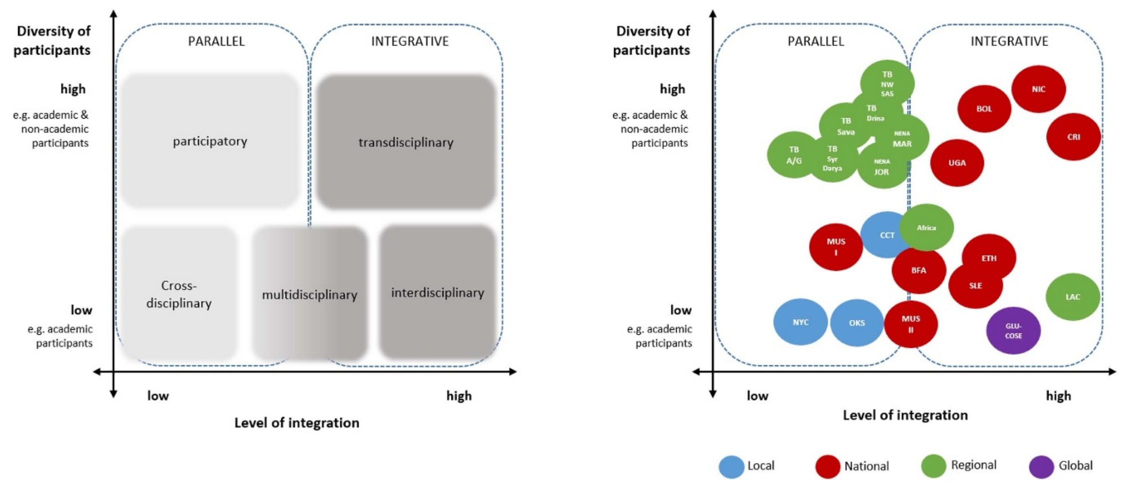
Figure 12. Involvement of stakeholders in the CLEWs studies reviewed.

covered extensively in this review, but implied in the following sub-section and presented in [11], is an analysis of the implications of different intensities of engagement. Taking the example of consultation, the intensity of involvement differs according to the number of stakeholders consulted (a core group versus a multi-sectoral pool), the frequency of consultation (e.g. throughout the project versus a consultation workshop), and their expertise background.

4.6. Integration across disciplines and stakeholder involvement

Nexus assessments can be arranged in several typologies of the disciplinary research, i.e. research on the integration of knowledge across and within disciplines. The understanding of the typologies can support the design of the assessments. This does not mean that certain levels of disciplinarity are preferred to others in CLEW assessments. What we would like to clarify here is that the level of disciplinarity relates to how the integration of different disciplines is performed and to the type of involvement of stakeholders in the assessment, number of participants involved in the systems, and the number of disciplines integrated, and the number of institutions involved in a study. Additionally, we aim at clarifying the use of disciplinary terminology in CLEWs and similar resource nexus assessments. A typology of disciplinarity enterprise depends on the level of integration of knowledge across disciplines. An assessment has a cross-disciplinary character when one discipline considers the perspective of another [144]. CLEWs analyses are generally multidisciplinary since they involve agents from different disciplines (e.g. energy systems, land use, water use, environmental science, climate, etc) who provide their perspective to a common problem. Suppose the assessment, required to solve the problem under investigation, results in the integration of knowledge and methods from various disciplines. In that case, the level of integration is high, and the study is considered interdisciplinary. These typologies, adapted from [144, 145], are illustrated in figure 13(a), in the horizontal axis. The engagement of different agents in the analysis (represented in the vertical axis in figure 13(a)) influences the type of disciplinarity if the participants belong to different areas of work or expertise. Depending on the level of knowledge integration (horizontal axis in figure 13(a)), the analysis can be classified as parallel or transdisciplinary. If the assessment involves several agents (or participants in figure 13(a)), but the level of integration is low, the assessment can be considered participatory. When the level of integration is high (high multidisciplinary or interdisciplinary), and stakeholder are actively engaged in the process (e.g. data collection, processing, modelling, co-development of reports and policy briefs, etc), then the assessment can be considered transdisciplinary, creating a unity of intellectual frameworks beyond the disciplinary perspectives. This is represented in the top-right corner of figure 13(a).

Analysing the 22 studies revised in this paper, we propose a distribution of the studies across the continuum of stakeholder involvement and knowledge integration. This is shown in figure 13(b). The mapping exercise is informed by elements described in the purpose of the assessments, the analytical approach, and stakeholder involvement. We find that regional studies aimed at fostering cooperation or regional development and involving a diverse pool of stakeholders of different decision levels, but who are engaged mostly through consultation approaches, are located in the top-left quadrant of the graph. Assessments situated in this space can be designated as participatory and multidisciplinary. Studies which focus mostly on academic research have a low level of participants' engagement. We find these studies in the bottom part of the chart, spread across the horizontal axis depending on the level of integration of knowledge. Here we see examples of local-level studies, the global CLEWs model, and the regional analysis of Africa [108] and LAC [122]. Also in this section, we find the first CLEWs study of Mauritius [15], Burkina Faso [43], and the direct application of CLEWs frameworks for exploratory exercises to promote discussion on the inter-sectoral implications of development ambitions (cases of Ethiopia and Sierra Leone). We find that low diversity of participants is not an impediment for integrated analysis, and these can be very valuable for knowledge advancement and as test cases. At the top-right corner of the graph, we find CLEWs studies which consider a reasonable level of integration across disciplines, and where stakeholders contribute more actively to the development of the analysis. Additionally, capacity building activities throughout the project development not only transfer knowledge across agents but assist in shaping the analysis and its relevance and robustness to address policy questions. This type of collaborative initiative benefits research by expanding the use of modelling tools. They create unique opportunities to test and



(a) (b)

Figure 13. Disciplinarity typologies in CLEW assessments: (a) relation between the involvement of stakeholders and integrative approaches (reprinted from [146], Copyright (2013), with permission from Elsevier. Based on Tress *et al* [145], and disciplinarity typologies in Stember [144]); (b) mapping of analysed studies in terms of disciplinarity typologies illustrated in figure 13(a). The abbreviations to Africa: BFU—Burkina Faso; BOL—Bolivia; CRI—Costa Rica; CCT—City of Cape Town; ETH—Ethiopia; LAC—CLEWs Latin America and the Caribbean; GLUCOSE— Global Least-cost User-friendly CLEWs Open-Source Exploraty model; MAU I—Mauritius study I (2013); MAU II—Mauritius study II (2016); NENA MAR—NENA Morocco study; NENA JOR—NENA Jordan study; NIC—Nicaragua; NYC—New York City; OKS—Oskarshamn municipality; SLE—Sierra Leone; TB A/G—Transboundary Nexus Assessment (TBNA) of the Alazani/Ganykh River; TB Drina—TBNA of the Drina River; TB Sava—TBNA of the Sava River; TB Syr Darya—TBNA of the Syr Darya River; and TB NWSAS—TBNA of the North-Western Saharan Aquifer System.

further develop tools tailored for the representation of specific systems and of their dynamics. Such type of assessments can be defined as transdisciplinary.

Different factors affect the level of integration and participation in CLEWs assessments. Aspects such as duration of the project, size of the analytical teams, the level of multidisciplinary expertise of the agents collaborating in the assessment, the number of disciplines involved, the diversity and number of agents included, the variety of participants (to name a few); will all influence the development of the project and its outputs. By understanding the significance of these factors, the teams involved in the planning of a nexus assessment can better design the studies and adjust the aim of the study to the level of integration which will possibly be achieved, or vice-versa. For example, a study can be planned with the objective of being used for a scoping mission for a prospective project. In this case, the level of integration would be possibly low (assuming there is a limited team of experts involved. Also, the preliminary scope and results of the project would be presented to a selected number of stakeholders to gather interest in the approach and possibly initiate a discussion on how to take the concept further in a specific context. This example would fall under a low level of integration and low to medium level of diversity of participants—and could be described as a cross-disciplinary assessment with limited stakeholder participation. Another example could be a regional assessment involving several countries (such as the transboundary case studies). In such type of studies, it may not be possible to engage, at a high level of collaboration, stakeholders from different countries, meaning that, at the most, a multidisciplinary and participatory approach would be feasible. However, if the study aims to more effectively engage participants, then the design of the assessment should include tasks and activities that would permit such level of involvement (e.g. themed workshops to discuss particular issues, creation of sectoral multi-country sector-focus teams, etc).

The level of integration and the diversity of stakeholders engaged in the assessments reviewed does not indicate to follow a distinct trend in terms of geographical scope. Exceptions are identified for regional—transboundary assessments that involve a high number of stakeholders from multiple sectors (top left quadrant)—and national cases, in their majority promoted by UNDESA/UNDP, which involve capacity building activities. Thus, stakeholder involvement in the assessments reviewed indicates to be closely linked to the format of the assessment, rather than to the context and scope of the case study.

5. Conclusions and recommendations

The CLEWs framework assists the exploration of interactions between (and within) the CLEWs via qualitative and quantitative means. Its institutional drive has been closing the gap between science and policy dimensions in its multiple applications and disseminating the importance of integrated planning. Additionally, the CLEWs framework has contributed to the development of knowledge of the nexus and systems-thinking to a wide range of audiences, including academia and at institutional levels. This has led to the development of a community of practitioners who are engaged in furthering the approach in terms of methods, applications, and knowledge transfer. The framework is organised in five main phases: (a) profiling of CLEW systems; (b) pre-nexus assessment; (c) analytical approach; (d) analysis of results; and (e) reporting and recommendations. These phases aim at guiding the analysis conducted in a CLEWs study. Iterations can occur between the steps, in particular between the last three. Different methods and processes can be deployed to achieve the objectives in each phase, and stakeholders can be engaged in a variety of ways (questionnaires, nexus dialogues, capacity building). The purpose of CLEWs studies spans through policy assessment, technology deployment and transition, resource management and efficiency, international cooperation and collaboration, climate studies and others purposes, e.g. academic research, framework dissemination and the establishment of communities of practice.

We have described and compared 22 historical, and ongoing, applications of the CLEWs framework, as well as of applications which contributed to its development. These are then compared in terms of geographic scope, purpose, interactions represented, analytical approach and stakeholder involvement. National and regional studies represent the majority of studies. This is explained by the fact that most were mandated by international organisations (mostly UN agencies), as well as the CLEWs frameworks origin and early evolution. The institutional link also facilitates the dissemination and expansion of the approach to other member states. In terms of purpose, CLEWs assessments generally explore several aims. Common foci include the cross-sectoral policy assessments, often coupled with resource efficiency and management. International cooperation and collaboration is the most common purpose in regional assessments. The CLEWs framework is system neutral (not biased towards a specific system). It is by assessing all the systems from the same standpoint that the impartiality is reached. The profiling of the systems, mapping of interactions, and identification of nexus challenges guide the representation of the systems in the analytical component of the work. The comparison of the cases indicates that studies at the national level include representation of more interactions and interactions more evenly distributed across CLEW systems.

Regional studies are also interactions-rich, but their representations vary considerably between studies. Local-level studies tend to focus on fewer systems and in more detail. At this scale, we find a relevant incidence of intra-linkages. In terms of analytical approach, types 2 (single-model) and 3 (soft-linking and mixed-method) are the most common approaches followed, with type 2 more frequent in national cases; and type 3, in regional. CLEWs assessments deploy various kinds of participatory approaches, and the engagement of stakeholders is often motivated by the aim and format of the evaluation (e.g. international cooperation and capacity-building programmes). Stakeholders ensure studies are context-relevant and assessments are conducted in line with local, national or regional trends or ambitions. Additionally, stakeholders are essential for the dissemination of the approach among their peers. We also find that high integration between disciplines and participation results in transdisciplinary analysis and thus, more opportunities for scientific processes to be dynamically incorporated in planning and policy design.

Several additional CLEW studies are ongoing or being initiated. As the community of practitioners expands, also the opportunity to enhance the approach arises. We leave here a few recommendations for the future of the framework and their users. First, it would be beneficial at different levels, to organise a community of practitioners, including the scientific community, stakeholders, institutional implementers, practitioners from other nexus approaches. Such identification of actors would contribute towards the multidisciplinary pool of experts for more effective dissemination of knowledge across geographies and sectors. Second, and related to the pool of experts, is the improvement of diffusion practices, in terms of increasing the academic output of analyses, policy briefs or project reports. Such outputs should be aligned and discussed between the partners involved in a CLEWs type analysis in terms of focus and purpose. This would ensure that the different communities can benefit from knowledge creation and the new practices established. Thirdly, a harmonisation of the terminology used in CLEWs studies is needed, including the establishment of standardised data repositories, the definition of key principles for assessments and/or the identification of publicly available sources for CLEWs assessments. Such materials and coherence could facilitate interoperability between modelling tools, dissemination and advancement of methods and tools to be implemented in the different phases of the framework—and facilitate improved dissemination. Also important is to create mechanisms and opportunities for methods and approaches, developed in specific scales, to be transferable across scales. For example, nexus dialogues in regional studies can be implemented at smaller levels. Regional assessments can inform the formulation of nationally-relevant scenarios but also be used as test-beds for national strategies. Moreover, regional models can be built from coupling national models. The vital role of co-development of assessments and the achievement of effective transdisciplinary practices should not be neglected. Capacity building and knowledge transfer are critical in this respect, with the side benefits of increased stakeholder participation towards a dynamic integration between policy and scientific processes. Some practitioners, who develop CLEWs analysis, advocate for the use of open data (when possible and applicable) and open modelling tools to increase the access to the tool and methods by wider audiences, although this is not an intrinsic characteristic of CLEWs applications. The aim is that the framework and, most importantly, its implementation is within reach to a variety of users (and teams) and that it contributes towards integrated policy and planning for sustainable development.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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