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A state-of-the-art review

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TOPICAL REVIEW

Analysing the development of the climate, land, energy, and water systems (CLEWs) modelling framework: a state-of-the-art review

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Abstract

This comprehensive state-of-the-art literature review explores recent scientific developments in climate, land, energy, and water systems (CLEWs) modelling by systematically analysing 41 peer-reviewed studies published between 2020 and 2024. This research uncovered insights into the evolving interdisciplinary landscape, revealing various trends, such as approximately 74% of studies publishing their data as open-access and 50% employing an open-source analytical tool, or tools, in combination with open-access data. This study identified four areas of significance: (1) the connections between CLEWs and the sustainable development goals, (2) how the CLEWs framework is linked to capacity development, (3) the critical interplay between energy and water systems, and (4) the transformative potential for comprehensive system integration using the CLEWs modelling framework. By pinpointing promising research directions such as soft-linking CLEWs models with geographic information systems, applying robust decision making methodologies, adapting the CLEWs framework to the city level, and highlighting the need to assess real world impact of CLEWs research, the review provides a strategic roadmap for future interdisciplinary research. Notably, the analysis emphasised the urgent need for enhanced institutional coordination and collaborative communities of practice, particularly for open-source modelling tools like the open-source energy modelling system, to further accelerate knowledge dissemination and foster innovative, integrated approaches to complex systemic challenges.

Acronyms

CLEWs	Climate, land, energy and water systems
IAEA	International Atomic Energy Agency
WEF	Water–energy–food (Nexus)
OSeMOSYS	Open-source energy modelling system
LEAP	Low emissions analysis platform
WEAP	Water evaluation and planning (system)
MESSAGE	Model for energy supply system alternatives (and their) general environmental impacts
TIMES	The integrated MARKAL-EFOM system (model generator)
AEZs	Agro-ecological zones
IOs	International organisations
UNDESA	United Nations Department of Social and Economic Affairs

SDG(s)	Sustainable development goals
U4RIA	Ubuntu, together with retrievability, repeatability, reconstructability, interoperability and auditability
PRISMA	Preferred reporting items for systematic reviews and meta-analyses
IMAGE	Integrated model to assess the global environment
SoSs	System of systems (framework)
GCMs	Global climate models
RCMs	Regional climate models
IAMs	Integrated assessment models
HE	Higher education
CCG	Climate compatible growth
GLUCOSE	Global least-cost user-friendly CLEWs open-source exploratory (model)
UNECE	United Nations Economic Commission for Europe
GWP-med	Global Water Partnership-Mediterranean
BAU	Business-as-usual
RCPs	Representative concentration pathways
CPA	Current practice approach
RDM	Robust decision making
TRBNA	Transboundary River Basins Nexus Approach
GISs	Geographic information systems
RDS	Robust decision support (process)
BC	British Columbia
BTH	Beijing–Tianjin–Hebei (BTH)
CMUA	Mega-large urban agglomeration of China
SLCP	Short-lived climate pollutant
NDP	National Decarbonisation Plan
NDC	Nationally determined contribution
TEMBA	The Electricity Model Base for Africa
MuSIASEM	Multi-scale integrated analysis of societal ecosystem metabolism
NWSAS	Northwestern Sahara Aquifer System
UWN	Upper White Nile
WEFE	Water–energy–food–environment
C-FEWSs	Climate-induced extremes on food, energy, and water systems
ISAM	Integrated science assessment model
FEWSs	Food, energy, and water systems
MUIO	Modelling user interface for OSeMOSYS
EMC	Energy modelling community
OnSSET	Open-source spatial electrification tool

1. Introduction

1.1. Background

CLEWs are inherently connected, and research on this nexus has expanded in scope since the late 2000s. The IAEA first presented the need to develop an integrated systems approach, for what they state as 'CLEW' systems and strategies, to meet sustainable development challenges [1]. The IAEA has further developed its material in recent years [2, 3]; showcasing how a CLEWs model study can be set up and citing how such models can be adapted to go beyond energy to represent the interlinkages between systems [3]. Accordingly, Bazilian *et al* [4] stated that there was a need to move towards a unified framework that considers energy, water and food, highlighting the need to develop robust analytical tools, conceptual models, and thorough data sets to project the future demand of energy, water and food.

CLEWs can be characterised as a nexus framework. Generally, nexus analyses, particularly on the WEF nexus, have evolved from a focus on water management to assessing urban challenges [5]. The WEF nexus was first conceptualised in 2008 before being adopted by the Water Security Council at the World Economic Forum in 2011 [6]. The WEF Nexus framework offers a holistic approach to understanding interconnected resource systems. By examining the trade-offs and synergies between water, energy and food sectors, this approach helps policymakers develop more integrated and sustainable cross-sectoral policies that account for broader social and environmental impacts [7].

CLEWs is a framework which can be applied to a wide range of modelling tools—it should not be confused with a tool or model itself. Examples of tools used in CLEWs quantitative studies include the OSeMOSYS [8], LEAP [9], WEAP [10] and MESSAGE [11], TIMES model generator [12], to name a few. However, challenges are faced when using such tools. Firstly, some tools are not fully open-source—i.e. the original source code is not freely available to use, study, change and distribute. This means studies can be difficult to reproduce and there is often limited knowledge of how to use the tool due to a lack of training materials available online, placing a barrier for people who wish to develop their skills [13]. However,

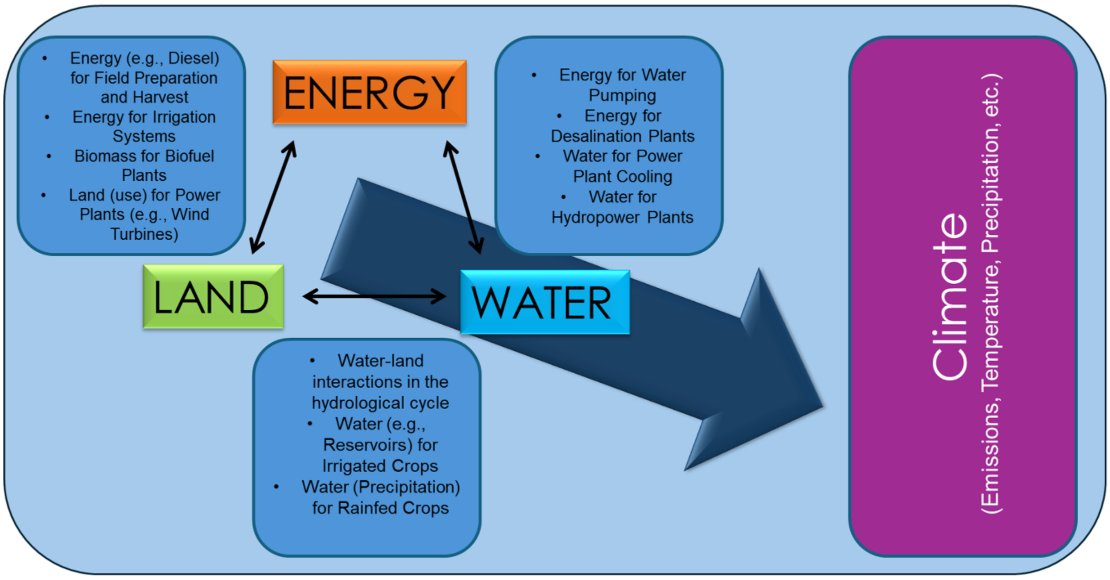

Figure 1. The climate, land, energy, and water systems (CLEWs) Framework. Adapted from [17], with permission from Springer Nature.

open-source is not the ultimate goal. It does not automatically improve usability or provide people with the best tools. Instead, the aim should be understandability [14], which open-source tools do not always achieve. This paper does, however, support the U4RIA goals, which represent Ubuntu, together with retrievability, reusability, repeatability, reconstructability, interoperability, and auditability [15], which provide a framework for energy system modelling, particularly in developing countries, focusing on making these models more transparent, robust and policy-relevant.

The first study to implement CLEWs as a framework was by Hermann *et al* [16] for Burkina Faso in 2012, which assessed agricultural intensification and bioenergy production. As Burkina Faso is resource-constrained, it was found that agricultural policy can have strong benefits for both the energy and environmental domains; for example, a reduced need to expand land for agriculture, resulting in less destruction of biodiversity. CLEWs was then presented as a new paradigm for resource assessments in 2013 [17] to combat the lack of efficient resource management in policy making. Figure 1 shows the first detailed depiction of the linkages between energy, water, and land use models, specifically in the case of the LEAP for energy and WEAP for water, and AEZs for land. It was stated that the CLEWs framework recognises that land, energy, and water resources are deeply interconnected and should be analysed together rather than separately. Instead of creating an entirely new integrated tool, CLEWs combines proven analysis methods for each resource type. It works by connecting separate specialised models that can exchange data with each other in a back-and-forth process, allowing them to work together while maintaining their strengths [17].

CLEWs was then implemented on a national scale by Welsch *et al* [18] for Mauritius in 2013. The authors assessed a scenario focusing on introducing a new crop with its characteristic fertiliser, whilst considering the water and energy demands of such a crop; concluding that, generally, a CLEWs approach will most likely add value to assessments where countries seek to implement integrated policies that have potential implications for cross-cutting resource systems. A CLEWs assessment can be valuable for countries that intend to implement integrated policies that incorporate a variety of resource systems [18].

CLEWs is becoming increasingly popular within country planning and IOs, such as the IAEA [3] and the UNDESAs [19]. Since 2017, these organisations have been frequently carrying out capacity development within the Global South [20], providing countries with the capabilities to apply the CLEWs framework to modelling scenarios and translate the results into policy recommendations. Additionally, the teaching of CLEWs has become embedded within HE [21, 22] and is now being placed into the curriculum in Global South countries [23]. The widespread and growing adoption of CLEWs highlights its value as a framework that enables multi-system analysis due to its holistic nature and flexibility to the purpose of the analysis, systems interactions to study, complexity in systems representation, and modelling framework. This is of particular relevance in the context of the SDGs [24]. The IAEA outlines SDGs 2, 6, 7, and 13 as the key SDGs [3], and their link to CLEWs is explained in table 1.

A systematic way of comparing CLEWs framework applications since the development of the framework was introduced in 2020 and outlined advances up to 2019 [20]. Crucially, the authors outlined the five main

Table 1. The sustainable development goals (SDGs) that have a direct link to the climate, land, energy, and water systems (CLEWs) framework. Adapted with permission from [3].

SDG	Connection to CLEWs
2: End hunger, achieve food security and improved nutrition, and promote sustainable agriculture	CLEWs can be implemented to model various scenarios concerning food production and agriculture, such as increased irrigated crops for higher yield.
6: Ensure availability and sustainable management of water and sanitation for all	CLEWs can be implemented to represent the water cycle and how the water balance is impacted by changing requirements, such as increased energy demand.
7: Ensure access to affordable, reliable, and modern energy for all	CLEWs can be implemented to assess sustainable and renewable energy pathways, such as increased energy production from wind power.
13: Take urgent action to combat climate change and its impacts	SDG 2, 6, and 7 need to be achieved in parallel, to be able to achieve SDG 13. Addressing the previous SDGs should go a long way to achieving SDG 13 and CLEWs can be used to assess many interlinkages between these goals.

phases in the CLEWs framework; these phases are (1) *CLEW systems' profiling,* (2) *pre-nexus assessment,* (3) *analytical approach,* (4) *analysis of results phase, and* (5) *reporting and recommendations.* The studies included in their review were very diverse in terms of scope, geographies, purposes, tools, methodology and who conducted the studies.

1.2. Purpose

This review paper builds upon previous work by Ramos *et al* [20], which presented applications and advances of the CLEWs framework until 2019. In the study, a total of 23 ongoing and complete CLEWs framework applications were analysed. The growing number of CLEWs studies since then motivates a new review of the recent literature to assess ongoing discourse around the framework. Along with this, one of the fundamental differences between this paper and Ramos *et al* [20] and where it contributes to a gap in the research, is the inclusion of other review papers on nexus assessment approaches, rather than just applications of CLEWs, and the exclusion of grey literature.

This paper goes beyond the need to find a systematic way of comparing assessments, the approach previously taken [20], instead focusing on how the presence of CLEWs studies in the scientific literature has evolved and consolidated. There is now a higher effort in transferring knowledge into the scientific literature, as opposed to the various types of grey literature. Previously, more grey literature and initiatives did not translate into scientific literature, but this study highlights the maturity of CLEWs in the scientific context whilst keeping its connection to practice. Further to this, analytically, this paper aims to not only provide context on key areas of research concerning CLEWs but also provide insight into the limitations of the framework and outline key areas for future research. Broadly, this will allow for collaboration opportunities, help to avoid duplication of efforts, and increase the awareness of ongoing trends, which is imperative as there is a growing need for CLEWs work, expanding both research and community.

1.3. Objectives and scope

This study is a state-of-the-art review to systematically evaluate recently published papers from 2020 to 2024 about CLEWs. CLEWs has become a framework implemented within technical assistance programmes; therefore, a large amount of grey literature is still produced around the topic. But to assess the maturity of the framework and ensure that only scientific literature is included, this study looks at only peer-reviewed articles found via Web of Science, Scopus, and Google Scholar.

The authors formulated the following research questions to provide a scope for the analysis of the chosen papers:

1. How has the field of CLEWs evolved in terms of paper type, data, tools, and geographical location from 2020 to 2024?
2. How does the CLEWs framework align with SDGs 2, 6, 7, and 13?
3. How has CLEWs been continuously used in capacity development and strengthening efforts?
4. Why, in particular, is the link between energy and water assessed within CLEWs studies?
5. How have the interlinkages within CLEWs been explored and developed since 2020?

This review synthesises the current state of knowledge regarding CLEWs, their methodological approaches, applications, and emerging challenges. Following on from this introduction, section 2 then gives a brief overview of the methodology used in this literature review. Section 3 presents key results from the bibliometric analysis. Followed by section 4, which presents key findings and insights from the content analysis, as well as limitations and areas for future research. Section 5 then concludes this review.

2. Methodology

The methodology applied in this study is that of a systematic literature review, which can be described as a review analysis that uses organised, step-by-step methods to collect and combine findings from multiple studies to answer a precise question [25]. Shaffril *et al* [26] previously outlined a set of guidelines for developing a systematic literature review for studies related to climate change adaptation. The guidelines are similar to those presented in the PRISMAs framework [25], which has been adopted in this study. This paper is methodologically novel as it is the first study to review the CLEWs scientific literature, applying an approach such as PRISMA. As stated previously, this study aims to build upon Ramos *et al* [20], in terms of reviewing studies published since that study, but taking a different approach. Ramos *et al* [20] provide a retrospective of CLEWs literature and state that no previous review of published literature had been undertaken, but they do not provide any methodology for how the studies included in their paper were chosen. Akpahou *et al* [27] is an example study that applies the PRISMA framework to perform a systematic literature review, discussing multiple modelling tools that are discussed within this study, such as OSeMOSYS [8] and LEAP [9]; they recommend the need to couple models more often to strengthen their capabilities.

As outlined in the introduction, five research questions were decided upon to guide this literature review. Research question one is used as the guiding question for the bibliometric analysis, presented in section 3. The categories for comparison included in the bibliometric analysis are: year published, open-access data, open-source tool, combining open-access with open-source, and geographical location. Research questions two through four form the guiding questions for the content analysis. The key findings and insights are then organised into the following categories and presented in section 4: SDGs and capacity development, link between energy and water, and encompassing the whole of the CLEWs framework. Finally, research question five provides the guiding question for our conclusions in section 5.

The applied methodology is easily replicable, and if replicated, can continue to provide a thorough overview of the development of CLEWs applications. Figure 2 shows the three key stages of this literature review. The first stage of the review corresponds to the paper identification process, which was based on the PRISMA framework by Page *et al* [25]. As outlined in the PRISMA 2020 statement, the framework 'provides updated reporting guidance for systematic reviews that reflects advances in methods to identify, select, appraise, and synthesise studies', along with a detailed 27-item checklist that can be used to support a systematic review. Once the final selection of papers was identified, the results were analysed, and then the content of the selected papers was examined.

The search engines Scopus and Web of Science were utilised for the paper identification process. In the search process, the keyword 'CLEWs' was used to search through the title, keywords and abstract of the literature. This was further cross-checked using the more detailed search terms 'CLEWs.' Figure 3 illustrates the implementation of the flowchart proposed in the PRISMA methodology [25].

Following the first search, 72 studies were found in Scopus and 183 in Web of Science. Three filters were applied to this first search: (1) *English-written documents,* (2) *open-access peer-reviewed papers only, and* (3) *publications between* 2020 *and* 2024. The date of publication refers to the online publication date. Scopus only shows one date of publication, whereas Web of Science shows *published* and *indexed*; therefore, the published date was followed when filtering through Web of Science. These filters were decided upon to refine the search and, due to a lack of resources, specifically to assess any non-English written documents. Applying these filters led to 55 papers being excluded from Scopus and 166 from Web of Science. During this stage, the abstract of each paper was analysed to assess the eligibility of the chosen papers further. It is also worth noting that 2020–2024 was selected as the period for reviewing papers to follow from the applications and advances of CLEWs until 2019 [20]. Finally, duplicates were removed, leaving a total of 19 papers from the screening process. Further, 22 other research papers identified through Google Scholar were included due to their eligibility for the criteria in the screening process. Therefore, a total of 41 papers were selected for the bibliometric and content analysis.

3. Results

The following section outlines the bibliometric analysis of the final 41 papers included in this literature review, which relates to Research Question 1. Figure 4 shows the split between *modelling* and *review* articles. Due to the CLEWs framework being a nexus approach, it is often mentioned within nexus-specific review papers, and, therefore, it was decided that these papers should be included in this review to gain an

Figure 2. Three stages outlined in the methodology.

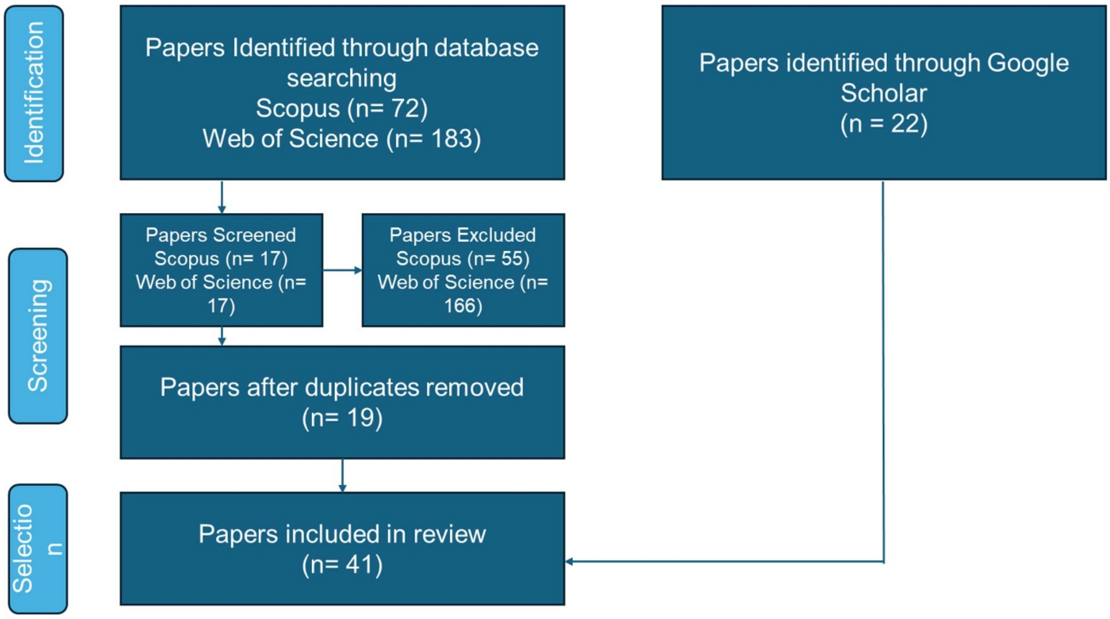

Figure 3. Workflow, based on PRISMA [25], implemented in the paper identification, screening, and selection process. Reproduced from [25]. CC BY 4.0.

understanding of the discourse around nexus approaches and how CLEWs fits into that discussion. Of the total 41 papers, 29 were modelling-focused and 12 were reviews. This literature review places CLEWs as the focal point and aims to provide insight into all aspects of recent CLEWs peer-reviewed research. As stated in section 2, the categories for comparison included in the results analysis are: year published, categorisation of papers, interlinkages, geographical scope, open-access data, modelling tool applied, and combining open-access with open-source. These categories were selected as an approach to finding recent trends within the scientific literature. *The supplementary file has all the information for each study included in this review.*

Two papers included in this review did not fit into the same categories as the rest. Mondal *et al* [28] was not explicitly a CLEWs modelling study as it entails the development of a new WEF-nexus model and its application in India, but it did highlight CLEWs as a current model or tool that can be used for WEF-nexus analysis. Therefore, this study was included as a review study in this analysis due to how CLEWs are discussed. Whereas Niet *et al* [29] did not include any explicit CLEWs modelling, rather it discussed CLEWs in the context of creating a community of practice around OSeMOSYS; therefore, this study was included as a modelling study.

3.1. Papers per year

Figure 5 highlights the number of studies per year included in the review. Modelling studies increased in number each year, peaking with 12 studies in 2024. Overall, studies increased too, despite a slight, unexplained decline in 2023. Previously, Ramos *et al* [20] discussed 23 ongoing and historic applications of CLEWs from 2012 to 2020. From these modelling-based applications, some had multiple references, including grey literature, totalling 43. Out of the 43 referenced pieces of literature, only 17 (39.5%), were peer-reviewed scientific literature. This averages to just over two peer-reviewed papers being published per year, even including some that had not been published at the time and are included in this review [30, 31]. Based on Ramos *et al* [20], there was also an increase in review-based studies from 2020 to 2022, which were

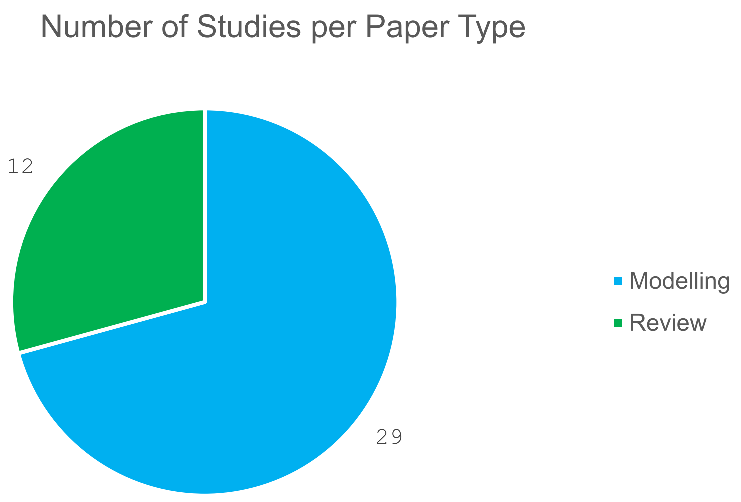

Figure 4. Studies included in the literature review split by paper type.

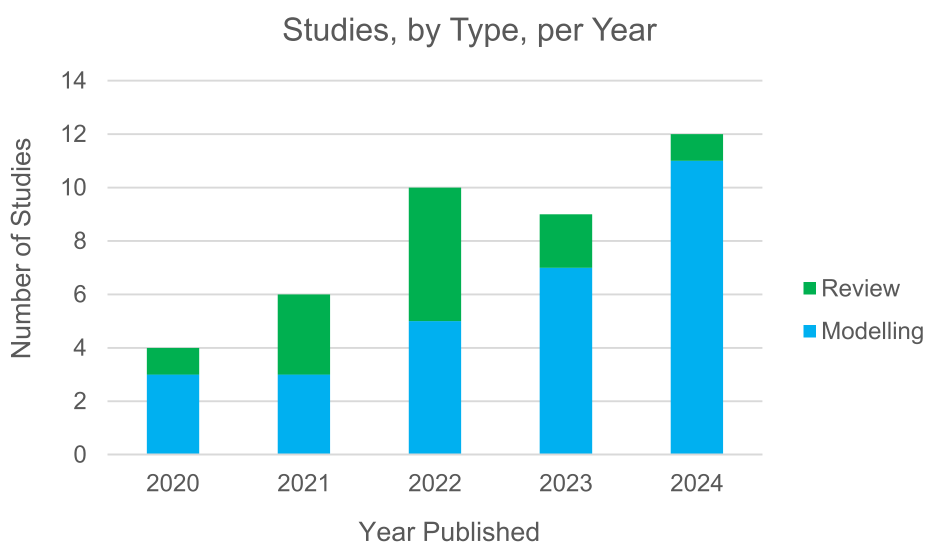

Figure 5. Number of studies per year included in the literature review.

not previously considered. The average of modelling and review, peer-reviewed papers published per year, included in this study, was just over eight. Comparatively, the average for modelling studies published per year in this study was just under six. This shows that the average of modelling scientific literature has more than tripled in the last 5 years when compared to Ramos *et al* [20].

3.2. Categorising the implementation of CLEWs

As shown in the previous section, papers have been categorised into *modelling* and *review*. These papers can also be further categorised to classify the context of how the CLEWs framework was applied or discussed. Firstly, they have been categorised by *conceptual* or *operational* framework use. Conceptual refers to the discussion of CLEWs as a concept and how it can be developed or implemented, but no such modelling takes place. Operational, although it may refer to conceptual ideas around CLEWs, refers to the use of the framework for modelling purposes. There are 23 studies categorised as operational implementation, and 18 studies categorised as conceptual implementation. Each study has then been further categorised into eight categories: pedagogy, RDM, social implications, geospatial modelling, framework development, institutional coordination, review and modelling, as shown in figure 6. For the sake of the analysis, the RDM, social implications, and geospatial modelling categories were created to highlight where a study has gone beyond the conventional, modelling, implementation of the CLEWs framework. Figure 6 highlights how, although modelling, in varying forms, is still the main implementation of the CLEWs framework, the reach extends beyond conventional modelling studies.

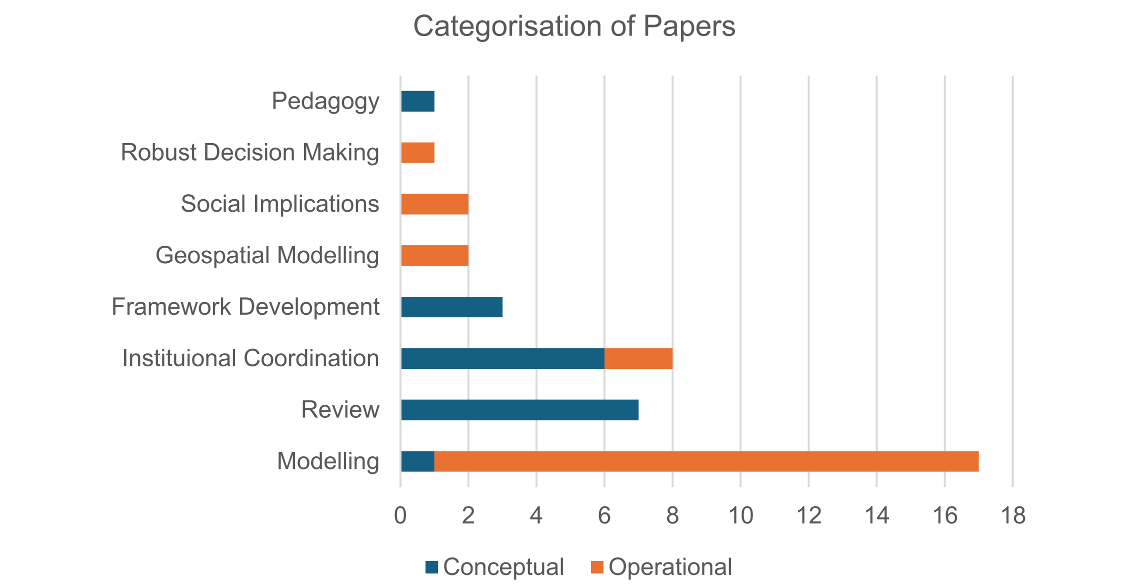

Figure 6. Categorisation of each study included in this review. Studies are first split into two categories: conceptual and operational; then they are divided into a further eight specific categories.

3.3. Interlinkages assessed per study

Out of the 41 studies included in this literature review, 19 studies were classified as not applicable because they do not implement or discuss the CLEWs framework in a way that assesses interlinkages between systems. Therefore, figure 7 highlights, out of the other 22 studies, how many studies include each type of interlinkage. Notably, energy is the most well-covered, including 21 studies assessing the link between energy and climate. Another significant finding is that land is the least covered aspect of the CLEWs system by studies included in this review. *The supplementary file has all the information the specifics of which interlinkages were assessed in each study included in this review.*

Di Leo *et al* [32] is an example study that covers all aspects of the CLEWs framework, yet they state in their conclusion that future work would build on the land(-food)-energy, and water–energy modules, or interlinkages, respectively. As well as this, other studies in this review look at the unique assessment of interlinkage. Ramos *et al* [20] address the unique interactions, referred to in this study as interlinkages, by the geographical scope of the studies included in their review. Similarly, Niet *et al* [33] discuss the CLEWs interlinkages, extending to the economy and separating food from land-use. Vinca *et al* [34] also compare models and outline which interlinkages those models assess.

3.4. Geographical scale and scope

Moreover, figure 8 shows the geographical scale of selective studies in the literature review. Despite being review-focused, two studies did have a geographical focus [35, 36], resulting in 12 studies which did not apply to specific scales. Out of the other 29 studies, 42% were national, 28% were regional, and 10% were global, continental, or local, respectively. Table 2 shows how many studies there were for each location. Five studies in the review were from South Africa. At the continental level, Africa had four, followed by Costa Rica with three. Then there were four countries with two studies. The rest had only one study each.

Figure 9 combines aspects discussed in section 3.3 with the geographical scale, of studies, highlighted in figure 8. The 22 studies included in figure 7 were classified according to whether they were a whole system representation or not. This is defined by including a minimum of one interlinkage from each aspect of the CLEWs framework, representing each of climate, land, energy, and water in some way. To gain a greater understanding of this, these findings were then combined with the geographical scale of each study. As shown in figure 9, the split between geographical scales has no real trends. However, national whole system studies represent the highest number, with seven studies, whilst all three continental studies included in this review did not cover the whole of the CLEWs framework. Further research could be undertaken to understand this insight, although it may highlight the difficulty of representing whole systems on such a large scale. Despite this, both global studies classified as applicable did cover the whole of the CLEWs framework; this therefore highlights that it is likely model-dependent. The single study defined as N/A by geographical scale but representing a whole system was Ramos *et al* [20], as they showcased how the CLEWs framework can be implemented with OSeMOSYS.

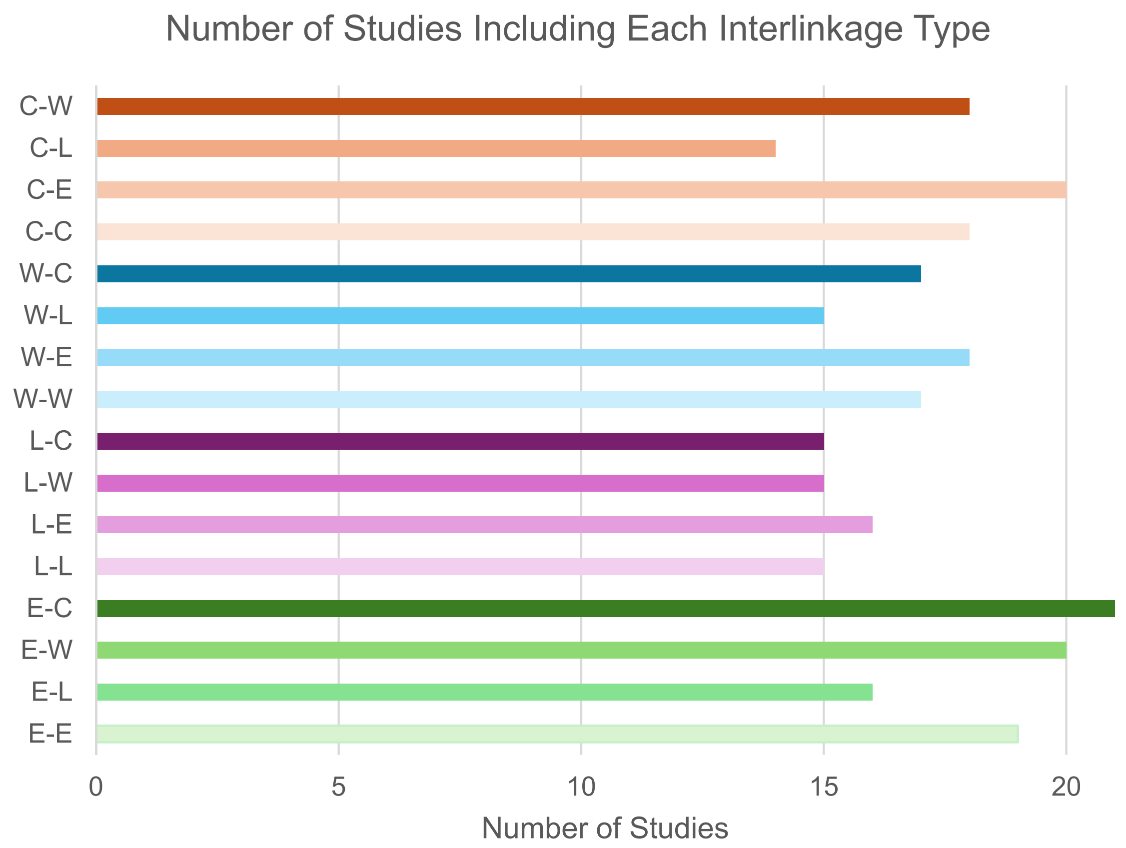

Figure 7. Number of studies included in this review that assess or discuss each interlinkage type, where C is climate, W is water, E is energy and L is land.

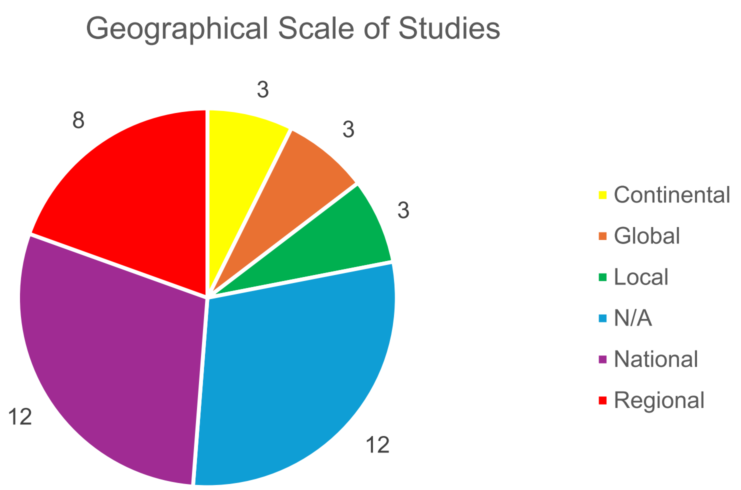

Figure 8. Geographical scale of (selective) studies in literature review. N/A refers to studies that were not scale-specific.

3.5. Open-access data

With evidence-based policymaking becoming a need for sustainable development, it is important to ensure transparency and reproducibility in modelling work [15]. Therefore, it is important to understand if researchers are using open-access data, as well as whether they are releasing the data they used as open-access. Figure 10 shows the split of all studies in the literature review. 13 studies did not apply to this as they did not involve the use of data for modelling, and one study did not have open-access data. The other 27 studies are split into (1) *fully open-access,* (2) *partially open-access, and* (3) *available on request.* Therefore, it shows that out of those 27 studies, just over 74% had fully open-access data.

Six studies stated that their data is available on request, as well as having a supplementary file [37, 41, 42, 49, 50, 53]. Groppi *et al* [53] explicitly stated that they could not share the hourly electricity data as it came

Table 2. Number of studies per region, which are countries or continents in this context. N/A refers to studies that were not geography-specific.

Region	Number of studies	Studies
Africa	4	[37–40]
Morocco	1	[30]
South Africa	5	[35, 41–44]
Uganda	2	[45, 46]
Canada	2	[47, 48]
China	1	[49]
Costa Rica	3	[47, 50, 51]
Europe	1	[52]
Italy	2	[32, 53]
United Kingdom	1	[22]
Global	2	[54, 55]
Lebanon	1	[56]
N/A	15	
Vietnam	1	[57]

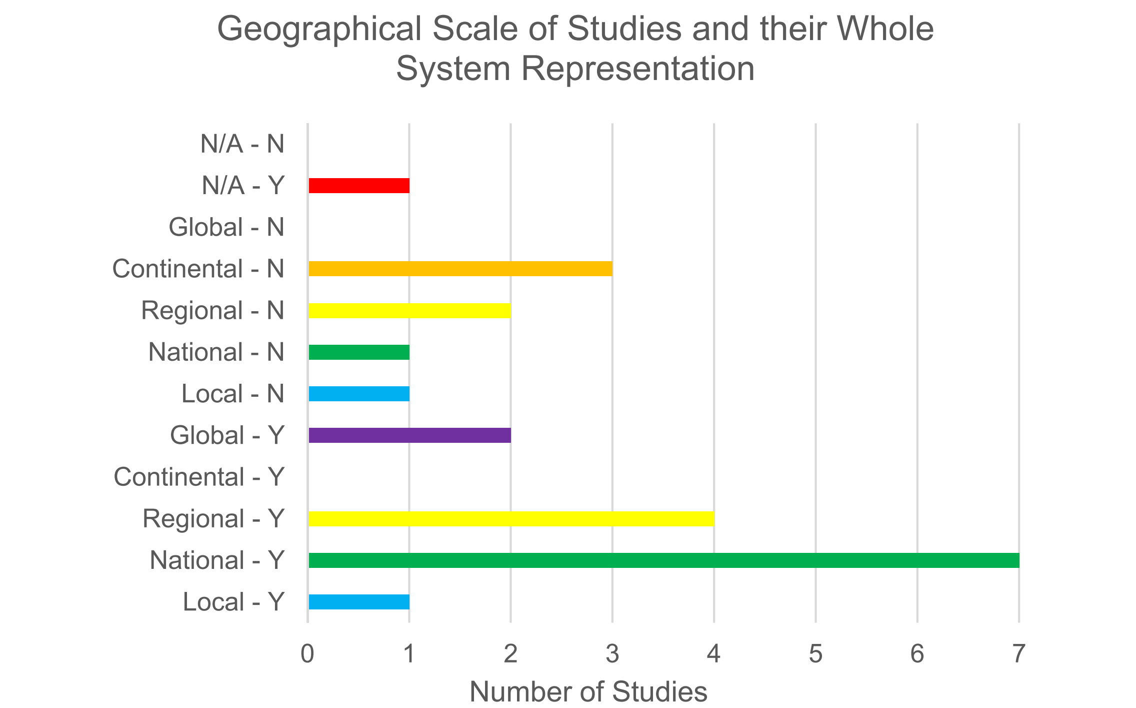

Figure 9. Combining geographical scale of studies with their whole system representation; whole system refers to a study that includes at least one interlinkage related to each of climate, land, energy and water. *Y* represents yes, and *N* represents No.

from the system operator; this was deemed partially open-access. Multiple studies stated that the data availability statement was not applicable, implying that no new data were used. Finally, Ramos *et al* [58], although a reference study that did not use any real-world data, was classified as open source as all data was included in the paper.

3.6. Modelling tools applied

Due to the flexibility of the CLEWs framework in terms of choice of quantitative methods, it can be applied using various modelling tools. Table 3, *in the appendix*, provides a description of each tool used in the studies identified in this literature review. It is important to note that OSeMOSYS [8], LEAP [9], and MESSAGE [11] are primarily used for single-sector energy modelling, but they allow for multi-sector or system representation, thus conveying flexibility in terms of sectoral representation. Whereas other tools, such as the IMAGE [59] and TIMES [12], already consider multiple sectors as tool modules that interact with each other automatically. WEAP [10], although the main focus is on water sector modelling, forcibly considers water–land interactions to model the natural availability of water and its use along different river catchments. It also allows for user-defined variables, which gives the tool some flexibility to account for aspects connected

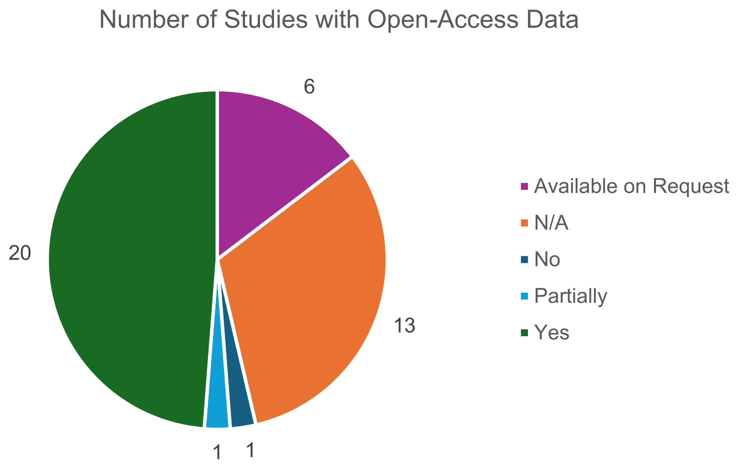

Figure 10. Number of studies that have open-access data, split into five categories. N/A refers to did not use data for modelling.

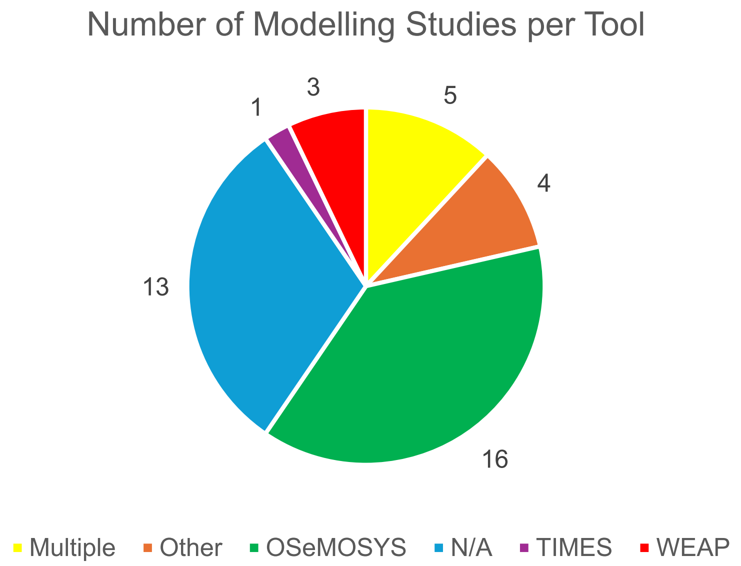

Figure 11. Number of (modelling) studies per tool, please refer to table 1 in the appendix for descriptions. N/A refers to a modelling tool not being applied.

to other systems. Also, tools can be soft- or hard-linked to other tools in multi-model frameworks; an example of this is Gebremeskel *et al* [60], which soft links OSeMOSYS to LEAP to assess electricity options for Ethiopia.

Figure 11 shows that out of the 41 studies in this review, 28 of them used a modelling tool, while the other studies did not apply a modelling tool or explicitly focus on the use of one. Sixteen (16) studies applied OSeMOSYS only, three of them applied WEAP only, one study applied TIMES only, five studies applied multiple tools, and four studies were categorised by *other*. The models included in the *other* category include the NWSAS GIS model, STELLA architect, SoSs frameworks, and Vensim PLE. One study discusses sustainability SoS frameworks [61], which are implemented to first assess, often on a numerical scale, the sustainability of a country or region; the stages of this begin with descriptive analysis, then conducting a sensitivity analysis based on specific indicators [56]. Finally, table 4, in the appendix, outlines the five studies that applied multiple tools. A single study used IMAGE and MESSAGE [54], one study combined LEAP and WEAP [62], two studies compiled LEAP, WEAP and (G)AEZ for regional applications in the context of the Buffalo River Catchment in South Africa [43, 44] and finally, one study used a combination of every available GCMs, not to be confused with general circulation models, and RCMs for the region [38].

3.7. Combining open-access with open-source

Out of the 29 modelling-focused studies in this literature review, only 13 studies combined open-access data with open-source tools, as shown in figure 12. Two studies were excluded [22, 29], as although both studies

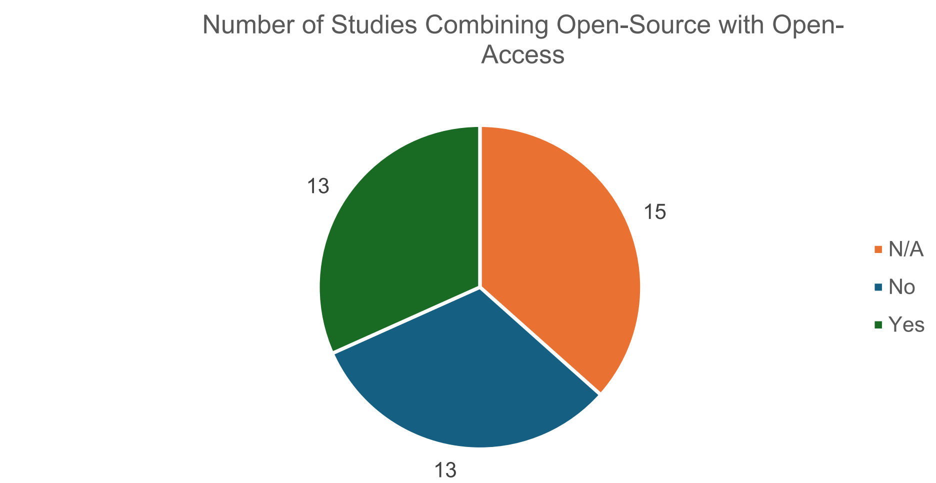

Figure 12. Number of selective, due to not explicitly using data or modelling tools, studies that combine open-access data with an open-source tool.

centred around an open-source tool, OSeMOSYS, they did not use any data for modelling but rather discussed data as part of their research. Then, Larsen *et al* [38], although they included open-access data, did not use a specific modelling tool, so it was also excluded. Therefore, out of the 26 applicable studies, 50% did not combine open-access data with an open-source tool, which does question the replicability of these CLEWs applications. However, as stated in section 3.2, approximately 74% of studies had fully open-access data, which is a high number and highlights, due to CLEWs being a framework, the potential for that data to be applied using a variety of tools. It may also be argued that 50% of studies applying open-source with open-access is a significantly high number, whereby in the future this figure may increase, but as long as the understandability of these open-source tools is a key focus [15]. T*he description of each tool in* table 3 *can be found in the appendix*.

4. Key findings and insights

The previous section outlined the increase in scientific literature being published and highlighted emerging trends. This section, in contrast, presents the key findings identified within the CLEWs-related scientific literature; as a reminder, this section aims to address research questions 2–5, defined in section 1.3.

4.1. CLEWs and the SDGs

The SDGs [24] are crucial to global development and provide a shared universal outlook that countries can strive to work towards. As highlighted in table 1, the IAEA presents SDGs 2, 6, 7, and 13 as the most important SDGs for CLEWs. Through this literature review, it was found that the SDGs are often included in the discussion around CLEWs and form a fundamental part of multiple studies [22, 33–35, 54, 63].

Firstly, Martindale *et al* [22] state that CLEWs modelling 'is well positioned to contribute to research questions that address the interlinkages between systems and the core drivers of UN policy, the SDGs'. Niet *et al* [63] highlight that best practice for the representation of the nexus and the SDGs should focus on datasets, in particular the complexity and accuracy of such datasets. Furthermore, to avoid black box models, best practices and a clear purpose should be top of the agenda for modelling studies [63]. Niet *et al* [63] created an evaluation framework for modelling, stating one of the 9 criteria to be addressing nexus interactions. Although they do not specify any of the SDGs, it is clear that their framework can be used within integrated modelling to achieve SDGs 2, 6, 7, and 13, which are outlined in table 1. Furthermore, Vinca *et al* [34] assessed CLEW models, not just the CLEWs framework. They state that despite integrated models being limited due to simplified data, models, such as CLEWs, which have a stronger focus on water or food scarcity, environmental protection, and or pollution, will have a greater impact when assessing the SDGs. Vinca *et al* [34] further state that CLEWs and models alike should be used to assess linkages to other SDGs such as industry and infrastructure.

Similarly, the link between the SDGs and the CLEWs nexus was assessed by Njuguna *et al* [35], focusing on South Africa, highlighting SDGs 2, 6, 7, and 13 as directly related to CLEWs, with 12 and 17 also being indirectly connected. Njuguna *et al* [35] provide 12 recommendations of how the CLEWs nexus could or should be utilised, including cross-sector partnership, encouraging open-source systems through capacity development, and promoting the use of artificial intelligence. Further to this, one novel approach combined two IAMs [58], versions of IMAGE and MESSAGE, to assess how short-term action can benefit the long-term SDGs. Tagomori *et al* [54] modelled three scenarios that combined the achievement of climate targets with the SDGs, the SDG scenario included additional measures to achieve food, water, energy, and biodiversity targets. In summary, this scenario shows that more equal distribution of food combined with healthier, less carbon-intensive diets, can lead to achievement of the SDGs outlined. However, the complexity of the SDGs and the interactions between CLEWs is shown by the fact that shifting towards less carbon-intensive diets whilst not ensuring food is equally distributed, could increase food insecurity.

Finally, Niet *et al* [63] examined all 17 of the SDGs, arguing that SDGs 16 and 17 cannot be met without open-source models and open-access data. They stated that, with relative ease, the definition of the CLEWs nexus should be expanded to cover other aspects such as health impacts (SDG 3). Overall, studies have shown that CLEWs contribute to more than just SDGs 2, 6, 7, and 13. The CLEWs framework can contribute to the SDGs by promoting cross-sector partnerships, uncovering interactions between goals, such as the link between health and food, and also by being open-source, making findings more universally accessible.

4.2. CLEWs and capacity development

Capacity development is emerging as a crucial aspect of development and helps to give ownership to countries, particularly within energy modelling. Nexus thinking, in the form of CLEWs modelling, has been outlined as a pedagogical approach [64] in a HE context [22] that can be used to address the challenges associated with the SDGs. Capacity development, for energy modelling, is often thought of or discussed in the Global South context [13, 21, 29]. Martindale *et al* [22], whilst discussing the relevance and link to the Global South, discuss an application in HE at Loughborough University in the United Kingdom. They conclude that CLEWs modelling, which promotes nexus thinking, provides a useful approach in teaching wicked problems [65], as it helps to foster an interdisciplinary approach to understanding complex, interconnected environmental challenges, enabling students to better understand the intricate relationships and dynamic interactions between CLEWs. Developing capacity at various levels, whether that is in HE or governmental institutions, benefits from the development of open-source, user-friendly modelling interfaces. Cannone *et al* [66] outlined clicSAND as an Excel-based interface for OSeMOSYS that is fully compatible with CLEWs, while Martindale *et al* [22] outlined how that interface could be used for OSeMOSYS and CLEWs within HE. Having access to open-source user-friendly interfaces for teaching and capacity development around modelling helps to skip upfront costs and often requires no coding knowledge for users. More recently there has been an effort to work with master's students on CLEWs-related theses, which are now transitioning into the development of peer-reviewed scientific literature.

Table 2 shows that roughly 65% of studies with a geographical focus were on the Global South, which can be explained by various reasons. The CLEWs framework was developed by the IAEA, a global organisation headquartered in Austria. The framework has since been applied largely by European-based academics, with a rising trend of publications focused on Global South countries. Firstly, this can be explained by the relatively small adoption of the CLEWs framework in research as a whole. Currently, CLEWs is still very much part of capacity development programmes, such as those discussed in the introduction, as it is viewed as a holistic approach to modelling multiple sectors and the interlinkages between them. Organisations such as UNDESA, IAEA, IRENA, and research groups, involving multiple universities, such as CCG [67], where academics work with academics in the Global South regularly, are at the forefront of this. Therefore, studies, such as Almulla *et al* [52], often arise from engagements between organisations or universities. Within the Global North, many countries have developed their way of thinking or already have a process in place. CLEWs is viewed as an opportunity for countries with low modelling capacity, as the framework can be relatively easily adopted and replicated for a country's needs. This is not to say that CLEWs is the only approach that can be taken in the Global South nor that countries in the Global South are not capable on their own, rather that continued engagement through capacity development programmes focus on the Global South, resulting in approximately 65% of the studies in this literature review that have a geographical focus, are studies in the Global South.

Broadly, capacity development on the use of CLEWs approaches contributes to knowledge transfer in different ways [20]. Another example is the GLUCOSE model, a global CLEWs model, which has been regularly deployed as an educational tool [55], where it is used to showcase pathways for global sustainable resource management, as well as how ready-made models can be used in capacity development. There are various forms of capacity development; one example, outlined by Ramos *et al* [21], is summer school training events. Such events may or may not be tied to a specific project, but are goal-oriented, requiring facilitators, or trainers, usually across a relatively short time frame, with accreditation or certification for participants at the end. This knowledge transfer can then support the transition to an integrated planning approach, with various enablers and opportunities outlined to combat barriers and challenges faced.

4.3. The link between energy and water

It was found that CLEWs studies initially focused on bioenergy and pathways for electricity systems [20], however, now, they highlight the different interactions, such as land–land, energy–land, and energy–water. Through this literature review, there was a clear research focus in studies on the interactions between energy and water. Soleimanian *et al* [68] state that despite CLEWs being able to utilise diverse models, including WEAP and MESSAGE, it is the limitations of the models that make CLEWs unsuitable for nexus analysis. For example, WEAP uses a lumped method to simulate the water subsystem, meaning it is difficult to determine many interlinkages in the water subsystem. Compiled methods are also suggested by Soleimanian *et al* [68], combining multiple tools, such as WEAP-LEAP, as a credible option; however, they further discredit WEAP as it cannot simulate the interconnection between groundwater and surface water.

Mujjuni *et al* [45] used WEAP to analyse water demand and usage. They found that the planned commissioning of the Karuma hydropower plant in 2023 will lead to the production contribution of plants along the River Nile increasing from 78% to 90%. Adaptation measures are proposed, centring on three major interventions, namely, robustness, responsiveness, and redundancy, to control environmental flow requirements. Due to Uganda's high reliance on the Nile for power production, making the country highly susceptible to drought events, Mujjuni *et al* [45] question the feasibility of implementing the adaptive measures modelled in their study.

Transboundary studies were highlighted as part of the institutional history of CLEWs [20], in particular river basin studies for the Drin River Basin [69]. The Drin River Basin has been a longstanding area of importance for organisations like the UNECE [70] and GWP-med [71]. Previously, Almulla *et al* [69] explored solutions to encourage transboundary hydropower cooperation in the Drina River Basin region. Almulla *et al* [52] further assessed these solutions by exploring the impact of climate change and floods on the electricity system, which is highly reliant on hydropower. An enhanced representation of the hydrological system and water storage was modelled to assess the changes in water availability imposed by a range of factors. It showed that the vulnerability of the Albanian power system to climate change is higher than in North Macedonia. They also state that the energy sector can play a significant role in mitigating the impact of floods; an integrated water–energy management plan could be a tool for each dam operator to plan. The model developed by Almulla *et al* [52] was used to showcase the importance of capacity development, as it can provide a wide range of insights to support water resource management in transboundary river basins. They do, however, state that their study is limited and could be improved through a sensitivity analysis of electricity imports, exploring a broader range of climate projections, and increasing the time resolution.

More recently, there has been a series of studies focused on the Buffalo River catchment in South Africa [41, 43, 44]. Firstly, applying GAEZ, LEAP, and WEAP, Dlamini *et al* [43] modelled a BAU scenario against a Policy Scenario, in combination with the RCPs, finding that water distribution inequalities will continue to persist due to the weaknesses of the water allocation plans for the catchment. Whereas in a follow-up study by Dlamini *et al* [41], they then used WEAP only to assess climate change impacts on surface water availability, again using the RCPs [72], it was found that annual precipitation is expected to increase, consequently leading to increased evapotranspiration and surface runoff. Finally, Dlamini *et al* [44], building upon previous studies, adopted a CPA; they then took a more CLEWs approach using the same combination of tools used previously. It was stated that the balance between the supply and demand of water is highly sensitive to climate change and the management of resources [44]. However, they do state that the effectiveness of WEAP and LEAP depends on the availability and granularity of data, also stating that their study is limited due to the exclusion of groundwater as a water source. Just as Dlamini *et al* [44] state, Soleimanian *et al* [68] discredit WEAP-LEAP. However, Mounir *et al* [73] aimed to address this, for a study of Phoenix, Arizona, by using different spatiotemporal resolutions. They found that increasing the temporal resolution from annual to monthly captured seasonal demands, improving the simulation of water allocations, and this meant the simulation of energy was, therefore, less sensitive to the model time step. Using finer spatial resolution in the domain improves the accuracy of modelling power plant water usage patterns.

At the local scale, one small island study using OSeMOSYS has been undertaken [53]. Groppi *et al* [53] used an hourly model to assess long-term water and energy supply strategies for the island of Favignana, Italy. One interesting technical finding was that no more storage capacity is required, as the current installed capacity is oversized. Furthermore, they state that small energy systems, like the one they built for their study, should provide a benchmark to test novel time series clustering methods for the construction of the typical day. However, in terms of reproducibility, both studies are limited due to their small scale, as they were only able to partially release the data as open-access, which is often the case with local governments who want to keep hold of their data [74].

Finally, a novel approach that introduced a stakeholder-driven and model-supported RDM framework was presented for Morocco [30]. Almulla *et al* [30] present what they call the enhanced participatory nexus methodology, which integrates the UNECE TRBNA [75] and RDS process, as an eight-stage process from a decision space to a final dissemination workshop. Their mixed methods approach utilised qualitative methods stated previously and quantitative methods, WEAP, and a GISs-based energy model. Applying this approach, they analysed 6 scenarios, which provided a wide range of technical findings. For example, the Moroccan national grid would supply the biggest share of the desalination and groundwater pumping energy demand, fully powering the desalination plant and powering roughly 70% of the groundwater pumps; however, due to Morocco being reliant on fossil fuels, the impacts must be mitigated. As this is the first study to apply RDM with CLEWs, others need to be able to replicate this study, fortunately, the full code used is available open source on GitHub [76]. RDM is also discussed in section 5 as an area for future research.

4.4. Interlinkages and beyond CLEWs

Rezaei Kalvani and Celico [77] outline CLEWs as a useful framework, in particular due to the possibility of providing vital information for climate change adaptation. As previously stated, CLEWs applications often focus on bioenergy and electricity systems pathways [20]. Two studies, both using OSeMOSYS, have been undertaken for Canada in recent years [47, 48]. Firstly, Kuling *et al* [47] assessed biofuels, specifically switchgrass, and their impacts on water and land use. They found that it would be water use, not land use, which would be the limiting factor for biofuel usage in Canada, concluding that biofuel usage would be more beneficial in sectors other than electricity, such as transportation. Also worthy of note is how they used OSeMOSYS Global [78] to supply electricity system data to their model. OSeMOSYS Global is an open-source, open-data model generator for creating global electricity system models. Barnes *et al* [78] state that compared to other existing global models, OSeMOSYS Global allows for full user flexibility in determining the time slice structure, as well as the geographical scope of the model and datasets.

Secondly, Arianpoo *et al* [48] look at the regional scale, producing the BC nexus model, to see how land use is impacted by electrification pathways. They conclude that the amount of land required to transform the energy system will increase by up to six times, under 100% electrification of the BC energy system. Finally, Sridharan *et al* [46] compared two scenarios—baseline and sustainable development—with the sustainable development scenario reducing biomass production to 50% of the total from 80% by 2050. Among many findings, they state the need for a change of thought; for example, in urban dwellings, despite access to electricity, they still use coal for cooking and heating. This is something fundamental that requires active engagement and learning to encourage such a change.

Studies were previously presented for Italy on the local scale discussing energy and water, but at the regional scale, one study used the Times Land-WEF model to analyse the agricultural system of the Basilicata Region, in Southern Italy [32]. Di Leo *et al* [32] stand out for two reasons. Firstly, land use is chosen as the guiding parameter for the optimisation process, specifically by land use demand by crop category and the number of livestock heads, which represent the end-user demands. Di Leo *et al* [32] attribute the impact of this approach to the potential for evaluating the effects of energy-environmental policy scenarios in terms of resource use, agricultural productivity, and the environmental impacts associated with farming. Then, secondly, Njuguna *et al* [35] is shaped by the *farm-to-fork* policy [79], which is a European Union policy focusing on making the food production system more sustainable. CLEWs is merely mentioned in the review of methods and tools; however, this study was included in this review due to the novelty of the approach and the particular focus on policy-driven modelling. Similarly, Li *et al* [49] look at the WEF resource supply shortage in the BTH CMUA. The significance of this study is not the research outcomes, but rather that this is the first Chinese-produced English language study to mention CLEWs, which could be a signifier for the future development of CLEWs research in this region.

Costa Rica has also become a focus country for CLEWS research in recent years, with three recent national studies undertaken [50, 51, 80]. These studies all exemplify exploring the whole CLEWs space and going beyond, for example, just land or water use impacts related to energy. Firstly, Victor-Gallardo *et al* [50] built on a previous study using the OSeMOSYS-CR model [81], using CLEWs to look at SLCP mitigation potential per sector, in particular methane, producing a value chain analysis to score policy instruments to find cross-sectoral synergies. This qualitative, value chain analysis assesses each sector, namely, transport, agriculture and land-use, solid waste, and industry; this analysis is designed to identify where interventions may be and follow six steps to do this. For example, step four, barrier identification and classification, involved experts from a range of public sectors being interviewed to respond to questions in a written questionnaire, presented in a virtual meeting. Despite the importance of bringing in key public stakeholders, Victor-Gallardo *et al* [50] state how private actors should participate in future discussions.

Chacon *et al* [80] utilised a different approach to assessing the impact of the transition to a net-zero economy on employment within CLEW sectors using Leontief multipliers, finding that it could produce 135 000 more jobs by 2050. This study highlights how the social impacts or benefits concerning CLEWs can be modelled and analysed to provide further insight for policymakers. More recently, 2 out of 18 modelled scenarios, BAU and NDP, were presented by Rodriguez-Acre *et al* [51] to highlight how CLEWs can support the updating of Costa Rica's NDC. They used workshops to formulate a locally produced model that was heavily influenced by stakeholders who were likely to use it. This is another example of increased stakeholder engagement within CLEWs modelling studies.

At the continental scale, a case study was presented using TEMBA [39], a model that is built within OSeMOSYS. Significantly, this study uses an open-source model and open-access data, to look at the connection between energy and water. Their findings outline how policy for sustainable and economic growth could be strengthened at the global and continental level, citing energy trade and country cooperation as key issues, by considering the interdependency of energy and water sectors in Africa. GLUCOSE, as previously discussed, is a global open-source CLEWs model built using OSeMOSYS [55]. A case study using the GLUCOSE model stated that due to its relatively simple structure, it can be easily used to produce several global scenarios [55]. Through analysing 4 scenarios, they found that consistent reliable data across sources for global models is difficult, meaning that the need to address data uncertainty is key.

One novel case study explores CLEWs using two parallel SoS frameworks [56], whereby these methodologies are explained in section 2 of this study. They highlight the most desirable electricity options for Lebanon, such as Offshore Wind and Solar PV, but most importantly, they highlight CLEWs as crucial to evaluating energy decisions without significant secondary impacts on valuable resources. One study used a systems dynamics approach to address resilience policies in Cape Town [42], whereas another used a combination of all GCMs to assess regional renewable energy planning in Africa [38]. Hoffman *et al* [42] cite MuSIASEM [82] as an alternative to CLEWs, although criticising both for their lack of user-friendliness or their limited applicability to a narrow range of use cases. Larsen *et al* [38] cite CLEWs as a model, alongside others such as TEMBA [39] and LEAP [9]; however, despite CLEWs being incorrectly referenced as a model, it is a framework that can be applied to build models using various tools.

OSeMOSYS has been discussed throughout this paper as a tool that can be used for the CLEWs framework. Ramos *et al* [58] showcase OSeMOSYS, using a reference study, as a tool that can be used to explore the whole CLEWs space, which is particularly useful for capacity development and knowledge transfer [21, 22, 58]. Shivakumar *et al* [57] use OSeMOSYS, truly encompassing the whole of CLEWs, and soft links a clustering tool, to aggregate spatial data, to a CLEWs model built in OSeMOSYS for Vietnam. It is stated that the applied methodology addresses the gap of spatial data representation in traditional system optimisation models, finding that the clusters represent a range of underlying data well; however, some limitations are stated, such as how the clustering tool does not consider seasonal differences in crop yields and multi-cropping methods.

An open-source GIS-based tool was created for a study on the NWSAS [40]. Almulla *et al* [40] state that their study was based on a combination of CLEWs and the TRBNA method [75], this coupling of approaches highlights the flexibility of the CLEWs framework. Spatial analysis is integrated throughout the approach; initially, spatial, and tabular datasets determine the specific location and coverage of irrigated cropland. Subsequently, the framework applies location-specific climate data and mathematical formulation to calculate water and power needs for groundwater irrigation across all identified locations. The final step assesses various electricity supply alternatives and recommends the least-cost arrangement for each location. Almulla *et al* [40] also highlight how research related to CLEWs can be strengthened when incorporating GIS tools, they state their methodology, despite its limitations, takes nexus analysis to the next phase.

Further to this, Taguta *et al* [83], in reviewing WEF nexus tools, highlight how CLEWs have the capabilities for soft linking to GIS tools. Significantly, Schlemm *et al* [37] used that review to develop indicators for the UWN, due to its important role in supporting ecosystem services and many millions of people in Eastern Africa, for the WEFE Nexus. They combined stakeholder engagement with a review of tools, finding the most significant gap was the exclusion of water quality and aquatic ecosystem indicators. This research demonstrates how integrating local stakeholders' perspectives and priorities can help create relevant, practical indicators that accurately reflect and address community-specific needs. Then, finally, by soft-linking GIS tools and involving stakeholders, the results obtained will have less uncertainty and increased real-world relevance.

Moving away from CLEWs specifically, a new framework was proposed by Vörösmarty *et al* [36] for use at the regional scale, C-FEWSs. C-FEWS is not an IAM itself, but does incorporate one, the ISAM [84]. They state that one reason for this new framework is that IAMs usually require large computational overhead and a team to execute the algorithms, as well as extending beyond the spatial domain of regional studies, as outlined in their study. Although the need for a framework on a regional scale may be true, the framework outlined and the coupling of methods suggested, add a higher level of complexity when compared with CLEWs, which would make this framework difficult to understand for a beginner. One of the benefits of CLEWs is that the framework is relatively straightforward, and recent capacity development efforts have improved the accessibility of applying it [21, 29, 58]. Jacobs *et al* [85] cite FEWS as a robust, CLEWs-related research topic, which is often used to discuss nexus thinking and cross-sector policy making; however, it does not address the impact of complex land use implications. Jacobs *et al* [85] further state the need to incorporate CLEWs perspectives into policy decisions and pose critical questions that can help to achieve transdisciplinary learning, citing integrative tools as the enabler for such learning. Further to this, Fard and Sarjoughian [62] present a novel, knowledge interchange broker composition modelling framework for simulating water, energy, and water–energy nexus systems. As with multiple studies that were included in this review, CLEWs were only mentioned once, under related work, however, this study explicitly discusses how this new framework can be used within LEAP and WEAP, which are two of the main tools used within CLEWs research.

4.5. Limitations

Firstly, this study is limited as it only looks at peer-reviewed literature and does not include any grey literature. This study highlights that CLEWs scientific literature has become more mature, but there are a vast number of studies not included that will still be of high quality and could provide insight into other themes of CLEWs research. Secondly, the bibliometric analysis was not carried out using specialist software, which can enhance the certainty of the results and provide further insights into recent trends. Further to this, this study is limited by language bias, as only English-language studies were selected for the review. This bias outlines a wider issue with the CLEWs framework, as currently the translation of material and knowledge into other languages is premature; this can be improved in the future by continued capacity development, incorporating other languages into these programmes. This study and future literature reviews of CLEWs scientific literature would benefit from using other search engines than just Scopus and Web of Science. These were selected due to their ease of use, and despite using two search engines, cross-referencing with another, potentially larger, database would further enhance the rigor of this review.

The CLEWs framework is limited by multiple issues, which often limit all variations of IAMs. Firstly, data availability and quality limit the true influence that results can have. Secondly, researchers not using open-source models reduce inclusivity and the ability to reproduce studies. This links to the previously mentioned U4RIA goals [23], which aim to improve the quality and usefulness of energy system modelling through transparent and collaborative practices that encourage knowledge sharing. Models can be complex and require high computation, so providing open-source tool applications like clicSAND for OSeMOSYS [66] and, more recently the MUIO [86], can be one, but not the only, way to reduce this. Finally, validation of data can be difficult to carry out, particularly when different data sources, for the same parameters, do not have corresponding values.

Implementation barriers, such as institutional coordination and capacity development needs, can limit the development of energy-related models generally, including CLEWs. Two studies [29, 87] outline how a community of practice can be created for open-source modelling tools, in the case of OSeMOSYS. This is something that has begun to be developed for CLEWs through the EMC [88], despite it being a framework and not a specific modelling tool. Having a community of practice, which includes people from different organisations working towards a similar goal, will help to streamline efforts and remove barriers at a faster rate.

4.6. Future research in the CLEWs domain

Various areas of future research need further development, arising from studies found in this literature review. One example [57] found in this literature review soft-links a CLEWs model to a GIS tool; soft-linking to GIS tools is a key area for future research, as it can improve the land-use representation of CLEWs models; this could, for example, provide location-specific least-cost electricity options concerning irrigated cropland [40]. Other examples [89, 90] showcase how soft-linking has been carried out successfully between OSeMOSYS and the OnSSET, to improve the spatial resolution of data used in energy system planning.

As outlined for Costa Rica by Chacon *et al* [80], CLEWs models can be linked to social impacts and benefits, such as employment or health benefits that arise from changing agricultural policy. This is an area that requires more development as it will allow policymakers, particularly in Global South countries, to understand the secondary impacts of the findings of modelling [91]. Furthermore, RDM can be used to further increase stakeholder influence on scenarios, and often long-term intended outcomes [92], but to achieve the best results, a sensitivity analysis must be undertaken [30, 93]. As outlined in this review, in recent years, there has been the development of various new frameworks concerning the WEF nexus [36, 62]. There is potential for comparing the insights CLEWs can deliver for specific challenges (e.g. resource scarcity, specific resource use conflicts, resilience to climate change under uncertainty) with those that the frameworks deliver.

From recent capacity development efforts in India, it became clear that there was interest in producing CLEWs models at the city level [94]. As shown in this study, CLEWs have been applied at the city scale, which was done using a Systems Dynamics approach [42]. Further to this, a recent study used OSeMOSYS to model 100% renewable energy pathways for the small state of Goa [95]. However, there are multiple limitations to modelling CLEWs on a city level. One issue, as is an issue more broadly, is the lack of reliable, suitable data available at such high spatial granularity; for example, defining how to represent the energy system can be difficult, as energy power plants often sit outside of city boundaries and are not usually responsible for powering only one city. Modelling studies also need to consider how to quantify uncertainty in several parameters across the CLEW systems and the impact it has on results; doing so will enhance the credibility of results, feasibility of scenarios, and reproducibility of such studies.

Future research can also expand the geographical coverage of CLEWs applications. As shown in table 2, despite the average of modelling scientific literature published per year tripling compared with Ramos *et al* [20], many regions, or groups of countries, of the world are yet to be studied. In this literature review, published studies show that from 2020 to 2024, there has been no coverage in South America or Central Asia, with limited coverage in the Middle East and Southeast Asia. Similarly, in Ramos *et al* [20], there was limited representation of these regions, with studies primarily focusing on Africa and Latin America. Research should also pursue how the CLEWs framework can be applied to more Small Island Developing States, such as Welsch *et al* [18] in 2013 for Mauritius, due to the geographical flexibility of the framework.

Finally, taking into consideration the positive implications a CLEWs-based study can highlight, it is key to understand how these implications transpire in the real world. Specifically in this review, modelling-focused studies and studies discussing the synergies and trade-offs of CLEWs with the SDGs highlight the potential impact of their findings. Therefore, future research on the real-world impact of CLEWs research could provide valuable insights to further increase the impact of CLEWs.

5. Conclusion

This state-of-the-art systematic literature review builds on a previous review of the literature [20] and provides a new update on the scientific literature published from 2020 to 2024, including a bibliometric analysis on which localities studies have been undertaken, what models are used, and the availability of data. What separates this from other studies is that it not only covers modelling applications of the CLEWs framework but also discusses the discourse around CLEWs within review-based studies.

The CLEWs framework has been continuously applied across the world, using various modelling tools, such as OSeMOSYS or WEAP, with just over 70% of modelling-specific studies using open-access data and more than half of these studies using open-access data combined with an open-source model. This study further showcases how the CLEWs framework can also be applied at varying scales. Ranging from small-island studies in Italy [53], to regional studies for the Buffalo River Catchment in South Africa [41, 43, 44], or at the global level using an open-source model [55]. It is also clear that the SDGs are heavily linked to CLEWs, in particular SDGs 2, 6, 7, and 13, as they promote nexus thinking, and CLEWs can be used as a framework or tool to encourage this [22]. It is evident that, when compared to Ramos *et al* [20], the link between energy and water, within CLEWs, is the most assessed and has continued to be so, particularly in river basin catchments.

As the CLEWs framework continues to be implemented and developed, it is key that the whole framework is utilised, as the interlinkages between systems have a great impact on each other. For example, the studies undertaken in Costa Rica [50, 51, 80] extended the use of the framework to look at social aspects related to CLEWs; this is a significant development, as previously these factors were not considered. Researchers and policymakers must continue to improve stakeholder engagement, encouraging local production of models through capacity development. One way this can be done is by increasing the adoption of open-source tools and open-access data, but this must be accompanied by increased understandability and usability of such open-source tools [15]. As well as focusing on addressing data uncertainty and the impacts it can have on model results [33]. This may then tend to enhance policy integration, with decreasing uncertainty of results, as it is important to see how these models can go beyond just academia and influence decisions made by policymakers.

Data availability statement

The data that supports the findings of this study are openly available in the supplementary files of this article.

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Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that have or could be perceived to have influenced the work reported in this article.

CRediT author statement

Kane Alexander: Conceptualisation, Formal Analysis, Methodology, Writing—Original Draft, Visualisation. **Naomi Tan**: Writing—Review & Editing, Supervision. **Fernando Plazas-Nino**: Writing—Review & Editing, Supervision. **Francesco Gardumi:** Writing—Review & Editing, Supervision. **Kamara Kuling:** Writing—Review & Editing. **Eunice Ramos:** Writing—Review & Editing. **Leigh Martindale:** Supervision. **Vivien Foster:** Supervision.

Declaration of Generative AI and AI-assisted Technologies in the Writing Process

During the preparation of this work, the author(s) used Grammarly to improve readability and language. Following the use of the tool, the author(s) further reviewed the content and take(s) full responsibility for the content of the publication.

Appendix

Table 3. Description of each tool used in the studies identified in this literature review.

Tool	Description	Open source	Link
OSeMOSYS	OSeMOSYS is an open-source modelling system for long-run integrated assessment and energy planning. It has been employed to develop energy systems models from the scale of continents, down to the scale of countries, regions, and villages. Designed to require no upfront financial investment, a fast-learning curve and little time commitment to operate, it is fit for use by communities of developers, modellers, academics up to policy makers.	Yes	https://github.com/OSeMOSYS/OSeMOSYS
WEAP	WEAP (water evaluation and planning) is a software tool for integrated water resources planning. It provides a comprehensive, flexible, and user-friendly framework for policy analysis. As a database, WEAP provides a system for maintaining water demand and supply information. As a forecasting tool, WEAP simulates water demand, supply, runoff, stream flows, storage, pollution generation, treatment and discharge, and instream water quality.	No	www.sei.org/tools/weap/
LEAP	LEAP, the Low emissions analysis platform, is a powerful and versatile software system for integrated energy, climate change mitigation, and air pollution abatement planning. Along with developing and supporting LEAP, SEI also develops LEAP-based scenario studies, helping policymakers and planners explore their options to meet future energy needs, mitigate climate change, and shift to a low-carbon development pathway.	Yes/no—context dependent	www.sei.org/tools/leap-long-range-energy-alternatives-planning-system/
TIMES	The TIMES (The integrated MARKAL-EFOM system) model generator was developed as part of the IEA-ETSAP (Energy Technology Systems Analysis Program), an international community that uses long-term energy scenarios to conduct in-depth energy and environmental analyses The TIMES model generator combines two different, but complementary, systematic approaches to modelling energy: a technical engineering approach and an economic approach. TIMES is a technology-rich, bottom–up model generator, which uses linear programming to produce a least-cost energy system, optimised according to several user constraints, over medium to long-term time horizons.	No	https://iea-etsap.org/index.php/etsap-tools/model-generators/times

(Continued.)

Table 3. (Continued.)

Tool	Description	Open source	Link
System of systems (SoSs) Framework	Farhat *et al* [56] two assessment approaches were used, each employing sets of decision-making criteria that address the most considerable energy sustainability issues and target levers that have a direct impact on the nation's scarcest resources. The first set, used in resource efficiency assessment (REA), represents a set of criteria that help to evaluate the impacts of the 16 electricity supply technologies. The second set of criteria, used in the sustainability performance assessment (SPA), represents the economic, environmental, societal, and technological considerations of energy planning in Lebanon. The SoS model of Madani *et al* [96], used in this study, implements a Monte Carlo multi-criteria decision-making (MC-MCDM) approach, which evaluates the desirability of the 16 electricity supply alternatives. The model used five different MCDM methods to add to the robustness of the ranking system and decrease the results' sensitivity to different notions of optimality.	N/A	See Farhat *et al* [56] and Madani *et al* [96]
IMAGE	The IMAGE modelling framework has been developed by the IMAGE-team under the authority of PBL Netherlands Environmental Assessment Agency. IMAGE is a computer model that simulates environmental consequences of human activities by integrating land, energy, climate, and policy models in one framework.	No	www.pbl.nl/en/image/home
MESSAGEix-GLOBIOM	MESSAGEix is a framework that can be used to develop and run many different models, each describing a different energy system. Models in the MESSAGEix framework can range from very simple (as in the Tutorials) to highly detailed (e.g. the MESSAGE-GLOBIOM global model). The framework can be applied to analyse scenarios of the energy system transformation under technical-engineering constraints and political-societal considerations.	No	https://docs.messageix.org/projects/models/en/latest/
Vensim PLE	Vensim Personal Learning Edition (PLE) is a version of Vensim that has been designed to lower the barriers to the beginning system dynamics modeller. This is a free version for academic and personal use, it has as simplified menus and dialogs, it contains fewer option settings, has a fixed tool set, contains fewer model-building tools and contains fewer of functions. The higher quality version is a paid version.	Yes	https://vensim.com/vensim-personal-learning-edition/
STELLA Architect	STELLA (Scalable Two-Level EvoLutionary Large Language Model Architecture) is a language model architecture that evolves both its overall structure and internal components simultaneously, aiming to create more efficient AI models with reduced computational costs.	No	www.iseesystems.com/store/products/stella-architect.aspx

(Continued.)

Table 3. (Continued.)

NWSAS (GIS model)	The NWSAS model is an open-source geographic information system (GIS) model focused on the Northwestern Sahara Aquifer System (NWSAS), which spans Algeria, Tunisia, and Libya. This model helps analyse and visualise data related to this important transboundary aquifer system, which is a critical water resource for the region. It was developed by KTH and helps assess water resources, land use, and related environmental factors in this arid region.	Yes	https://github.com/KTH-dESA/NWSAS
Global agro-ecological zones (GAEZ)	Global agro-ecological zones (GAEZ) is a methodology and database developed by the FAO and IIASA that assesses agricultural resources and potential worldwide. It evaluates land suitability, potential crop yields, and production limitations based on climate, soil, and terrain conditions, helping inform agricultural planning and food security decisions.	Yes	https://gaez.fao.org/

Table 4. Outline of which studies applied multiple tools, and the relevant supporting information.

Title	Authors	Coverage	Tools	Open access data	Open source & open access
The water–energy–food (WEF) nexus as a tool to develop climate change adaptation strategies: a case study of the Buffalo River catchment, South Africa.	Dlamini *et al* [41]	Regional	LEAP, WEAP, (G)AEZ	Yes	No
Climate policy and the SDGs agenda: how does near-term action on nexus SDGs influence the achievement of long-term climate goals?	Tagomori *et al* [54]	Global	IMAGE, MESSAGEix-GLOBIOM	Yes	No
A knowledge interchange broker composition modelling framework for simulating water, energy, and water–energy nexus systems	Fard *et al* [62]	N/A	LEAP, WEAP	N/A	N/A
Modelling the water supply-demand relationship under climate change in the Buffalo River catchment, South Africa	Dlamini *et al* [44]	Regional	LEAP, WEAP, (G)AEZ	Yes	No
Renewable energy planning in Africa: robustness of mean and extreme multi-model climate change patterns in solar PV and wind energy potentials	Larsen *et al* [38]	Continental	Combination of every available combination of global (GCMs) and regional climate models (RCMs).	Yes	No

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References

[1] IAEA 2009 Annex VI: seeking sustainable climate land energy and water (CLEW) strategies (International Atomic Energy Agency) (available at: https://inis.iaea.org/records/67hdn-p7a25)

[2] IAEA 2020 Integrated assessment of climate, land, energy, and water (available at: www.iaea.org/publications/13558/integrated-assessment-of-climate-land-energy-and-water)

[3] IAEA 2024 The climate, land, energy, and water framework: a methodology handbook p 5 (available at: www.iaea.org/publications/15686/the-climate-land-energy-and-water-framework)

[4] Bazilian M *et al* 2011 Considering the energy, water, and food nexus: towards an integrated modelling approach *Energy Policy* **39** 7896–906

[5] Lazaro L L B, Bellezoni R A, Puppim de Oliveira J A, Jacobi P R and Giatti L L 2022 Ten years of research on the water-energy-food nexus: an analysis of topics evolution *Front. Water* **4** 859891

[6] Mohtar R H 2022 The WEF nexus journey *Front. Sustain. Food Syst.* **6** 820305

[7] Albrecht T R, Crootof A and Scott C A 2018 The water-energy-food nexus: a systematic review of methods for nexus assessment *Environ. Res. Lett.* **13** 043002

[8] Howells M *et al* Open-source energy MOdelling SYStem (OSeMOSYS) (available at: https://github.com/OSeMOSYS/OSeMOSYS)

[9] Stockholm Environment Institute Low emissions analysis platform (LEAP) (Stockholm Environment Institute) (available at: www.sei.org/tools/leap-long-range-energy-alternatives-planning-system/)

[10] Stockholm Environment Institute Water evaluation and planning system (available at: www.sei.org/tools/weap/)

[11] IAEA Model for energy supply strategy alternatives and their general environmental impact (MESSAGE) (available at: chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/www-pub.iaea.org/MTCD/Publications/PDF/Pub1718_web.pdf)

[12] International Energy Agency Energy Technology Systems Analysis Program (IEA-ETSAP) The integrated MARKAL-EFOM system (TIMES) model generator (available at: https://iea-etsap.org/index.php/etsap-tools/model-generators/times)

[13] Cannone C *et al* 2023 Addressing challenges in long-term strategic energy planning in LMICs: learning pathways in an energy planning ecosystem *Energies* **16** 7267

[14] Pfenninger S 2024 Open code and data are not enough: understandability as design goal for energy system models *Prog. Energy* **6** 033002

[15] Howells M *et al*, 2021 Energy system analytics and good governance-U4RIA goals of energy modelling for policy support

[16] Hermann S, Welsch M, Segerstrom R E, Howells M I, Young C, Alfstad T, Rogner H H and Steduto P 2012 Climate, land, energy, and water (CLEW) interlinkages in Burkina Faso: an analysis of agricultural intensification and bioenergy production *Nat. Resour. Forum* **36** 245–62

[17] Howells M *et al* 2013 Integrated analysis of climate change, land use, energy, and water strategies *Nat. Clim. Change* **3** 621–6

[18] Welsch M *et al* 2014 Adding value with CLEWS–modelling the energy system and its interdependencies for Mauritius *Appl. Energy* **113** 1434–45

[19] UNDESA Modelling tools for sustainable development: CLEWs (available at: https://un-modelling.github.io/modelling-tools/)

[20] Ramos E P *et al* 2021 The climate, land, energy, and water systems (CLEWs) framework: a retrospective of activities and advances to 2019 *Environ. Res. Lett.* **16** 033003

[21] Ramos E P, Gardumi F, Niet T, Sridharan V, Alfstad T, Pappis I, de Strasser L, Shivakumar A, Howells M and Rogner H H 2022 Capacity development and knowledge transfer on the climate, land, water, and energy nexus *Handbook on the Water-Energy-Food Nexus* (Edward Elgar Publishing) pp 149–77

[22] Martindale L, Cannone C, Niet T, Hodgkins R, Alexander K and Howells M 2023 Empowering tomorrow's problem solvers: nexus thinking and CLEWs modelling as a pedagogical approach to wicked problems *Energies* **16** 5539

[23] Taita Taveta University (TTU), Kenya 2024 TTU LinkedIn: CLEWs modelling training workshop (available at: www.linkedin.com/posts/school-of-mines-and-engineering-taita-taveta-university_clews-modelers-activity-7268135983966007297-6f0J?utm_source=share&utm_medium=member_desktop)

[24] UNDESA Sustainable development goals (SDGs) (available at: https://sdgs.un.org/goals)

[25] Page M J *et al* 2021 The PRISMA 2020 statement: an updated guideline for reporting systematic reviews *BMJ* **372** n71

[26] Shaffril H A M, Samah A A and Samsuddin S F 2021 Guidelines for developing a systematic literature review for studies related to climate change adaptation *Environ. Sci. Pollut. Res.* **28** 22265–77

[27] Akpahou R, Mensah L D, Quansah D A and Kemausuor F 2024 Energy planning and modelling tools for sustainable development: a systematic literature review *Energy Rep.* **11** 830–45

[28] Mondal K, Tantuway R B, Chatterjee C and Singh R 2023 Development of a water-energy-food nexus model for multiscale studies *Irrig. Drain.* **72** 1356–73

[29] Niet T, Shivakumar A, Gardumi F, Usher W, Williams E and Howells M 2021 Developing a community of practice around an open-source energy modelling tool *Energy Strategy Rev.* **35** 100650

[30] Almulla Y, Ramirez C, Joyce B, Huber-Lee A and Fuso-Nerini F 2022 From participatory process to robust decision-making: an agriculture-water-energy nexus analysis for the Souss-Massa basin in Morocco *Energy Sustain. Dev.* **70** 314–38

[31] Ramirez C, Almulla Y, Joyce B, Huber-Lee A and Nerini F F 2022 An assessment of strategies for sustainability priority challenges in Jordan using a water–energy–food Nexus approach *Dis. Sustain.* **3** 23

[32] Di Leo S, Tortorella M M, Fortes P, Viccaro M, Cozzi M, Romano S and Cosmi C 2024 The TIMES Land-WEF model: an integrated analysis of the agricultural system of the Basilicata region (Southern Italy) *Energy Nexus* **15** 100315

[33] Niet T, Arianpoo N, Kuling K and Wright A S 2022 Increasing the reliability of energy system scenarios with integrated modelling: a review *Environ. Res. Lett.* **17** 043006

[34] Vinca A, Riahi K, Rowe A and Djilali N 2021 Climate-land-energy-water nexus models across scales: progress, gaps, and best accessibility practices *Front. Environ. Sci.* **9** 691523

[35] Njuguna A, Mohamed B and Ngila J C 2021 Smart climate resilient and efficient integrated waste to clean energy system in a developing country: industry 4.0 *African Handbook of Climate Change Adaptation* (Springer) pp 1053–80

[36] Vörösmarty C J *et al* 2023 The C-FEWS framework: supporting studies of climate-induced extremes on food, energy, and water systems at the regional scale *Front. Environ. Sci.* **11** 1069613

[37] Schlemm A, Mulligan M, Tang T, Agramont A, Namugize J, Malambala E and van Griensven A 2024 Developing meaningful water-energy-food-environment (WEFE) nexus indicators with stakeholders: an Upper White Nile case study *Sci. Total Environ.* **931** 172839

[38] Larsen M A D, Bournhonesque J, Thiery W, Halsnæs K, Hattermann F F, Hoff H, Salack S, Adenle A and Liersch S 2024 Renewable energy planning in Africa: robustness of mean and extreme multi-model climate change patterns in solar PV and wind energy potentials *Environ. Res. Commun.* **6** 015001
[39] Pappis I, Sridharan V, Howells M, Medarac H, Kougias I, Sánchez R G, Shivakumar A and Usher W 2022 The effects of climate change mitigation strategies on the energy system of Africa and its associated water footprint *Environ. Res. Lett.* **17** 044048
[40] Almulla Y, Ramirez C, Pegios K, Korkovelos A, Strasser L D, Lipponen A and Howells M 2020 A GIS-based approach to inform agriculture-water-energy nexus planning in the Northwestern Sahara Aquifer System (NWSAS) *Sustainability* **12** 7043
[41] Dlamini N, Senzanje A and Mabhaudhi T 2023 Assessing climate change impacts on surface water availability using the WEAP model: a case study of the Buffalo River catchment, South Africa *J. Hydrol.* **46** 101330
[42] Hofmann V S, Egieya J M, Parker Y, Gorgens J and Goosen N J 2024 Impact of resilience policies on Cape Town's water-food nexus: a system dynamics approach *Bull. Natl Res. Centre* **48** 102
[43] Dlamini N, Senzanje A and Mabhaudhi T 2023 The water–energy–food (WEF) nexus as a tool to develop climate change adaptation strategies: a case study of the Buffalo River catchment, South Africa *J. Water Clim. Change* **14** 4465–88
[44] Dlamini N, Senzanje A and Mabhaudhi T 2024 Modelling the water supply-demand relationship under climate change in the Buffalo River catchment, South Africa *PLOS Clim.* **3** e0000464
[45] Mujjuni F, Betts T and Blanchard R 2023 Uganda's hydropower system resilience to extreme climate variability *Climate* **11** 177
[46] Sridharan V, Shivakumar A, Niet T, Ramos E P and Howells M 2020 Land, energy, and water resource management and its impact on GHG emissions, electricity supply, and food production-insights from a Ugandan case study *Environ. Res. Commun.* **2** 085003
[47] Kuling K, Barnes T, Shivakumar A, Brinkerink M and Niet T 2022 Applying the open-source climate, land, energy, and water systems (CLEWs) model to Canada *Energy Strategy Rev.* **44** 100929
[48] Arianpoo N, Islam M E, Wright A S and Niet T 2024 Electrification policy impacts on land system in British Columbia, Canada *Renew. Sustain. Energy Trans.* **5** 100080
[49] Li W *et al* 2024 Development path for China's mega-large urban agglomerations based on the water-energy-food nexus *J. Cleaner Prod.* **472** 143481
[50] Victor-Gallardo L, Roccard J, Campos P, Malley C S, Lefevre E N and Quiros-Tortos J 2022 Identifying cross-sectoral policy synergies for decarbonization: towards short-lived climate pollutant mitigation action in Costa Rica *J. Cleaner Prod.* **379** 134781
[51] Rodríguez-Arce M, Angulo-Paniagua J, Victor-Gallardo L, Roccard J, Quirós-Tortós J, Alexander K and Howells M 2024 Integrated climate, land, energy, and water framework to support the nationally determined contribution updating process *Energy Strategy Rev.* **51** 101316
[52] Almulla Y, Zaimi K, Fejzić E, Sridharan V, De Strasser L and Gardumi F 2023 Hydropower and climate change, insights from the integrated water-energy modelling of the Drin Basin *Energy Strategy Rev.* **48** 101098
[53] Groppi D, Kannan S K P, Gardumi F and Garcia D A 2023 Optimal planning of energy and water systems of a small island with an hourly OSeMOSYS model *Energy Convers. Manage.* **276** 116541
[54] Tagomori I S, Harmsen M, Awais M, Byers E, Daioglou V, Doelman J, Vinca A, Riahi K and van Vuuren D P 2024 Climate policy and the SDGs agenda: how does near-term action on nexus SDGs influence the achievement of long-term climate goals? *Environ. Res. Lett.* **19** 054001
[55] Beltramo A, Ramos E P, Taliotis C, Howells M and Usher W 2021 The global least-cost user-friendly CLEWs open-source exploratory model *Environ. Model. Softw.* **143** 105091
[56] Farhat R A, Mahlooji M, Gaudard L, El-Baba J, Harajli H, Kabakian V and Madani K 2020 A multi-attribute assessment of electricity supply options in Lebanon *Food-energy-water Nexus Resilience and Sustainable Development: Decision-making Methods, Planning, and Trade-off Analysis* (Springer) pp 1–27
[57] Shivakumar A, Alfstad T and Niet T 2021 A clustering approach to improve spatial representation in water-energy-food models *Environ. Res. Lett.* **16** 114027
[58] Ramos E P, Sridharan V, Alfstad T, Niet T, Shivakumar A, Howells M I, Rogner H and Gardumi F 2022 Climate, land, energy, and water systems interactions–from key concepts to model implementation with OSeMOSYS *Environ. Sci. Policy* **136** 696–716
[59] IMAGE—Integrated Model to Assess the Global Environment PBL netherlands environmental assessment agency (available at: www.pbl.nl/en/image/home)
[60] Gebremeskel D H, Ahlgren E O and Beyene G B 2023 Long-term electricity supply modelling in the context of developing countries: the OSeMOSYS-LEAP soft-linking approach for Ethiopia *Energy Strategy Rev.* **45** 101045
[61] Phillis Y A, Kouikoglou V S and Manousiouthakis V 2010 A review of sustainability assessment models as system of systems *IEEE Syst. J.* **4** 15–25
[62] Fard M D and Sarjoughian H S 2024 A knowledge interchange broker composition modelling framework for simulating water, energy, and water-energy nexus systems *Simulation* **100** 657–82
[63] Niet T, Arianpoo N, Kuling K and Wright A S 2021 Embedding the United Nations sustainable development goals into energy systems analysis: expanding the food-energy-water nexus *Energy Sustain. Soc.* **11** 1–12
[64] Grossman P 2009 Research on pedagogical approaches in teacher education *Studying Teacher Education* (Routledge) pp 437–88
[65] Simm D, Marvell A and Mellor A 2021 Teaching "wicked" problems in geography *J. Geograph. Higher Educ.* **45** 479–90
[66] Cannone C *et al* 2024 clicSAND for OSeMOSYS: a user-friendly interface using open-source optimisation software for energy system modelling analysis *Energies* **17** 3923
[67] Climate Compatible Growth (CCG), FCDO-funded research group (available at: https://climatecompatiblegrowth.com/)
[68] Soleimanian E, Afshar A and Molajou A 2022 A review on water simulation models for the WEF Nexus: a development perspective *Environ. Sci. Pollut. Res.* **29** 79769–85
[69] Almulla Y, Ramos E, Gardumi F, Taliotis C, Lipponen A and Howells M 2018 The role of energy-water nexus to motivate transboundary cooperation: an indicative analysis of the Drina River Basin *Int. J. Sustain. Energy Plan. Manage.* **18** 3–28
[70] United Nations Economic Commission for Europe (UNECE) (available at: https://unece.org/)
[71] Global Water Partnership, GWP-Mediterranean (GWP-med) (available at: www.gwp.org/en/GWP-Mediterranean/)
[72] International Panel on Climate Change (IPCC) Representative concentration pathways (RCPs) (available at: www.ipcc.ch/report/ar6/syr/downloads/report/IPCC_AR6_SYR_SPM.pdf)
[73] Mounir A, Guan X and Mascaro G 2021 Investigating the value of spatiotemporal resolutions and feedback loops in water-energy nexus modeling *Environ. Modelling Softw.* **145** 105197
[74] Gascó-Hernández M, Martin E G, Reggi L, Pyo S and Luna-Reyes L F 2018 Promoting the use of open government data: cases of training and engagement *Gov. Inf. Q.* **35** 233–42

[75] De Strasser L, Lipponen A, Howells M, Stec S and Bréthaut C 2016 A methodology to assess the water energy food ecosystems nexus in transboundary river basins *Water* **8** 59

[76] KTH-dESA/FAO Climate, land, and energy analytical study of potential Nexus Issues in Jordan and Morocco (available at: https://github.com/KTH-dESA/FAO)

[77] Rezaei Kalvani S and Celico F 2024 Analysis of pros and cons in using the water–energy–food nexus approach to assess resource security: a review *Sustainability* **16** 2605

[78] Barnes T, Shivakumar A, Brinkerink M and Niet T 2022 OSeMOSYS global, an open-source, open-data global electricity system model generator *Sci. Data* **9** 623

[79] European Commission Farm to Fork Strategy, European Green Deal (available at: https://food.ec.europa.eu/horizontal-topics/farm-fork-strategy_en)

[80] Chacon M J S *et al* 2023 The regional employment implications of a net-zero economy in Costa Rica under uncertainty *Adv. Clim. Change Res.* **14** 988–99

[81] EPERLab OSeMOSYS-CR model (V2) (available at: https://github.com/EPERLab/osemosys-cr-v2)

[82] Giampietro M, Mayumi K and Ramos-Martin J 2009 Multi-scale integrated analysis of societal and ecosystem metabolism (MuSIASEM): theoretical concepts and basic rationale *Energy* **34** 313–22

[83] Taguta C, Senzanje A, Kiala Z, Malota M and Mabhaudhi T 2022 Water-energy-food nexus tools in theory and practice: a systematic review *Front. Water* **4** 837316

[84] Niyogi D, Liu X, Andresen J, Song Y, Jain A K, Kellner O, Takle E S and Doering O C 2015 Crop models capture the impacts of climate variability on corn yield *Geophys. Res. Lett.* **42** 3356–63

[85] Jacobs K, Holway J, Hanak E, Quay R, Sternlieb F and Udall B 2022 Impacts and opportunities at the climate–land use–energy–water interface: an urgent call for dialogue *JAWRA J. Am. Water Resour. Assoc.* **58** 411–9

[86] CCG and UNDESA, Modelling user interface for OSeMOSYS (available at: https://github.com/ClimateCompatibleGrowth/MUIO)

[87] Gardumi F *et al* 2018 From the development of an open-source energy modelling tool to its application and the creation of communities of practice: the example of OSeMOSYS *Energy Strategy Rev.* **20** 209–28

[88] Climate Compatible Growth Energy modelling community (EMC) YouTube playlist (available at: https://youtube.com/playlist?list=PLhLN8V8JSUnJgt4SIE7gnXXncVEaXh0Ir&si=Fn0s3tubjlPRZ9Rr)

[89] Pappis I, Sahlberg A, Walle T, Broad O, Eludoyin E, Howells M and Usher W 2021 Influence of electrification pathways in the electricity sector of Ethiopia—policy implications linking spatial electrification analysis and medium to long-term energy planning *Energies* **14** 1209

[90] Pappis I 2022 Strategic low-cost energy investment opportunities and challenges towards achieving universal electricity access (SDG7) in forty-eight African nations *Environ. Res.* **2** 035005

[91] Tan N *et al* 2025 Data-to-deal: developing an energy modelling analytical workflow to enhance political and financial decisions (pre-print)

[92] Pathways 2050 Using robust decision-making to develop long-term strategies (available at: https://2050pathways.org/resource-hub/using-robust-decision-making-to-develop-long-term-strategies/)

[93] Usher W, Barnes T, Moksnes N and Niet T 2023 Global sensitivity analysis to enhance the transparency and rigour of energy system optimisation modelling *Open Res. Eur.* **3** 30

[94] British High Comission in India, 2024 Capacity development between Anna University, the British High Commission in India, and Climate Compatible Growth (available at: www.linkedin.com/posts/ukinindia_this-uk-india-project-in-tamil-nadu-is-a-activity-7254109773745278976-0lev?utm_source=share&utm_medium=member_desktop)

[95] Heredia-Fonseca R, Kumar S, Ghosh S, Thakur J and Bhattacharya A 2024 Modelling a 100% renewable energy pathway in developing Countries: a case study of the State of Goa, India *Energy Convers. Manage.* **315** 118800

[96] Madani K, Shalikarian L, Hamed A, Pierce T, Msowoya K and Rowney C 2015 Bargaining under uncertainty: a Monte-Carlo fallback bargaining method for predicting the likely outcomes of environmental conflicts *Conflict Resolution in Water Resources and Environmental Management* (Springer) pp 201–12