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Climate, Land, Energy and Water systems interactions – From key concepts to model implementation with OSeMOSYS

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ABSTRACT

The Climate, Land, Energy and Water systems (CLEWs) approach guides the development of integrated assessments. The approach includes an analytical component that can be performed using simple accounting methods, soft-linking tools, incorporating cross-systems considerations in sectoral models, or using one modelling tool to represent CLEW systems. This paper describes how a CLEWs quantitative analysis can be performed using one single modelling tool, the Open Source Energy Modelling System (OSeMOSYS). Although OSeMOSYS was primarily developed for energy systems analysis, the tool's functionality and flexibility allow for its application to CLEWs. A step-by-step explanation of how climate, land, energy, and water systems can be represented with OSeMOSYS, complemented with the interpretation of sets, parameters, and variables in the OSeMOSYS code, is provided. A hypothetical case serves as the basis for developing a modelling exercise that exemplifies the building of a CLEWs model in OSeMOSYS. System-centred scenario analysis is performed with the integrated model example to illustrate its application. The analysis of results shows how integrated insights can be derived from the quantitative exercise in the form of conflicts, trade-offs, opportunities, and synergies. In addition to the modelling exercise, using the OSeMOSYS-CLEWs example in teaching, training and open science is explored to support knowledge transfer and advancement in the field.

1. Introduction

Nature is characterised by the interconnectedness of its systems. The increasing use of resources, determined by management, political and economic decisions, and driven by global economic development and population growth, has implications for the planet and human activities. In 1972, Limits to Growth (Meadows et al., 1972) provided the first account of the interdependence of systems globally through a modelling analysis. Based on (Forrest et al., 2020), the model dynamically examined the interconnections between five variables: population, natural resources, capital investment, capital investment in agricultural fraction, and pollution. In the early 1990s, Florin and Gabriel (1991) proposed a methodology for Integrated Resource Management, motivated by the limited availability of food, energy and mineral resources. Several decades later, Rockström et al. (2009) identified nine planetary boundaries that, if crossed, could question life in the planet as we know it. These studies highlight the influence of decisions on Earth systems and how natural, social and economic systems are linked. They also demonstrate that science-based evidence plays a vital role in decision-making.

The integrated assessment of resource systems (or Nexus analysis) is an approach that can support sustainable development-oriented decision making through the identification of potential cross-systems trade-offs, opportunities, conflicts and synergies. The study of the impact of climate change on precipitation and consequences to the energy sector in Canada, published in 1988, is one of the first examples of a Nexus analysis (Newell et al., 2019). Since then, the Nexus approach concept has expanded rapidly, particularly from the 2010s (Bazilian et al., 2011; Hoff, 2011; Ringler et al., 2013). It differs from initial integrated

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assessment efforts in inter- and transdisciplinary practices and the broader investigation of decisions' impacts across systems (Newell et al., 2019; Roidt and Avellán, 2019). The Climate, Land, Energy and Water systems (CLEWs) framework is a Nexus approach that examines CLEWs interactions. It originated from a conceptual analysis of a biofuel chain (IAEA, 2009), and it has been applied to more than 30 contexts worldwide (Ramos et al., 2021a; UNDESA / UNDP, 2017).

This paper showcases a simple example of a CLEWs-type quantitative analysis using one modelling framework - the Open Source energy Modelling SYStem (OSeMOSYS) (Howells et al., 2011). The example is informed by CLEWs approach practice[1]. Current literature on OSeMOSYS-CLEWs applications does not explain the modelling approach in detail for it to be easy to understand, accessible and adoptable. The paper aims to transfer the basics of CLEW systems modelling firstly by clarifying model use and analysis; secondly, describing practical entry-points of quantitative analysis to new Nexus practitioners, supporting the adoption (and advancement) of the Nexus approach.

1.1. *Multi-systems integrated modelling approaches for Nexus assessments*

Several modelling tools enable performing integrated assessments at different spatial scales, often supported by documentation that assists their learning and application. This is the case of global Integrated Assessment models (IAMs), such as GCAM (JGCRI, 2020), MESSAGE-GLOBIOM (IIASA, 2020a; Popp et al., 2017) or IMAGE (Stehfest and Kram, 2014), and other discussed in (Johnson et al., 2019). At a more targeted scale, and local level, Martinez-Hernandez et al. (2017) introduce a water-energy-food and ecosystem simulation (NexSym) tool, initially developed for the example of an eco-town in the United Kingdom. With a focus on the water-energy Nexus, (Khan et al., 2017) present the SPAtial and Temporal NEXus – Water Energy (SPATNEX-WE) model, a hard-linked partial equilibrium linear optimisation model that analyses the energy flows through the life cycle of water systems and vice-versa. A water-energy-food-climate nexus open-source optimisation tool to support water infrastructure planning, WHAT-IF, is described by Payet-Burin et al. (2019), together with its application to the Zambezi River basin. WHAT-IF is also applied to the analysis of a multi-purpose reservoir in Central Asia (OECD, 2018). Another open optimisation modelling platform is the NExus Solutions Tool (NEST), developed by (IIASA, 2020b; Vinca et al., 2020). Tool functionalities and features, which consider the use of open-access spatial data in the multi-scale integrated assessment of land, water and energy resources, are explained in detail in its application to the Indus River basin nexus. Systems Dynamics Models (SDM) are another approach to multi-systems nexus modelling (Brouwer et al., 2018). For a detailed comparison of modelling tools in CLEW assessments, we recommend the review by Vinca et al. (2021).

Different analytical approaches have been used with the CLEWs framework, from qualitative methods to quantitative approaches that consisted of model linking, accounting frameworks or a single-model approach. The latter was identified in nine of the 22 case studies reviewed by (Ramos et al., 2021a) and applied at various spatial scales. Several of these studies used the OSeMOSYS modelling framework[2].

Modelling tools are essential elements in the quantitative analysis of the Nexus. They vary in complexity, can be coupled or developed as integrated single model approaches. Numerous reviews of Nexus applications and frameworks have been published in the past decade, from which we summarise aspects related to quantitative approaches. The need for complementarity between biophysical modelling with economic models and social and behavioural elements is highlighted by Kling et al. (2017) and Albrecht et al. (2018). Neglecting socio-economic dimensions could affect the buy-in of key institutional actors with decision and dissemination influence (Newell et al., 2019). Tools and methods to perform Nexus analyses are needed (Albrecht et al., 2018; Zhang et al., 2018). These should be flexible and accommodate a diversity of contexts and interactions (Endo et al., 2017; McCarl et al., 2017), and be accessible to various audiences (e.g. practitioners, decision-makers and researchers). Accessibility could be enabled by capacity building (Kling et al., 2017; Zhang et al., 2018), or a collective development approach (Dargin et al., 2019). Less complex tools (or "simple" tools) could assist the identification of Nexus "hotspots" in the initial stages of an assessment, in contrast to more complex and detailed tools (Dargin et al., 2019). Several authors mention the challenges of reconciling systems' scales (Kling et al., 2017; Iwanaga et al., 2021), the dynamic representation of model elements and uncertainty (McCarl et al., 2017; Zhang et al., 2018; Little et al., 2019), models' detail or the partial depiction of systems (Endo et al., 2017; Kling et al., 2017; Zhang et al., 2018), the integration of bottom-up (more technical) and top-down (system level) approaches (Little et al., 2019), and boundary setting (Zhang et al., 2018).

A subtle tactic is required to facilitate the adoption by decision-makers. Methods and tools should be improved in terms of "easiness, accessibility, usefulness and accuracy of the analyses" (McCarl et al., 2017) to reduce the gap between policy and research (Zhang et al., 2018) and effectively support decision-making processes (Albrecht et al., 2018). Newell et al. (2019) identify that exploring the impacts of multiple Nexus triggers can blur the understanding of Nexus dynamics; thus, clarifying systems' dynamics and modelling approach is essential. Additionally, the outputs produced should be sectorally relevant (Kling et al., 2017) and advance cooperation and coordination in Nexus insights (McCarl et al., 2017).

This paper meets the identified need of clarifying systems' dynamics and modelling approaches of Nexus assessments. It provides an explanatory approach to modelling, ultimately aiming to reduce the research and policy gap. It does so by discussing the model representation of CLEW systems via a simple modelling example. The rest of the paper is organised as follows. The conceptualization and structuring of the model are described in Section 2. In Section 3, results elucidating the model's function as an evidence-based tool are presented, along with its use in entry-point applications to the Nexus approach. Section 4 concludes.

2. An OSeMOSYS-CLEWs analysis: from key concepts to the analysis of cross-system dynamics

This section introduces key concepts of the representation of CLEW systems (2.1), the modelling tool used in this work (2.2) and the illustrative simple case (2.3), including of cross-systems dynamics depicted (2.4). The section concludes with an overview of the scenarios investigated indicative of the analyses that can be performed (2.5).

2.1. *Mapping systems and their interactions: the reference CLEWs diagram*

When building an energy systems model, a diagram known as "Reference Energy System" (RES) is drafted. The RES represents the main system's elements to be included in the modelling representation following a bottom-up resources to uses approach, i.e. resources are represented to the left and uses or services to the right. Examples are shown in Fig. 1. In the RES, lines represent energy carriers (e.g. coal, diesel, electricity), and boxes represent activities or processes (e.g. mining, electricity

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[1] The exercise consolidates knowledge from practice since the first OSeMOSYS-CLEWs example (Alfstad et al., 2016), teaching and capacity development activities initiated in 2017 (ICTP, 2017; KTH-dESA, 2017a), and later applications.

[2] In the single-model format, OSeMOSYS-CLEWs applications include the cases of Mauritius (Alfstad et al., 2016; Alfstad and UNDESA, 2016), Ethiopia (UNECA and ACPC, 2018), Sierra Leone (Gardumi et al., 2019; UNECA and ACPC, 2018), Uganda (Sridharan et al., 2020), Nicaragua (Ramos et al., 2021a), Costa Rica (Quirós-Tortós et al., 2020), Bolivia (Peña Balderrama et al., forthcoming), the Philippines (Niet and et. al, forthcoming); and global (Beltramo et al., 2021; Taliotis et al., 2016a).

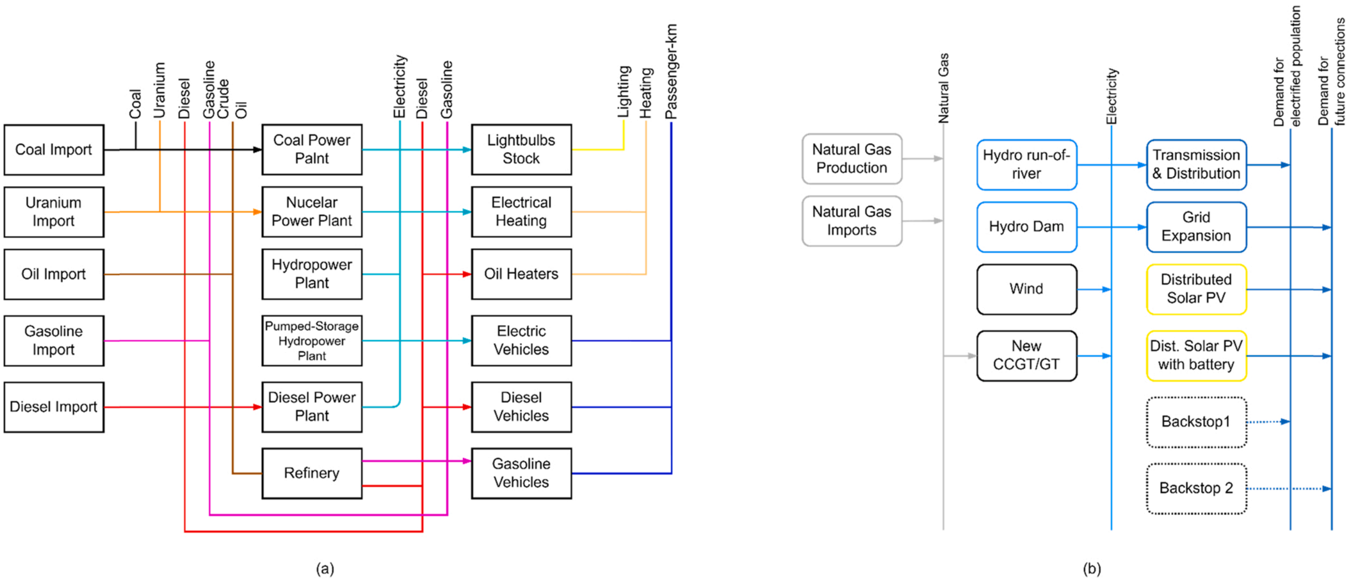

Fig. 1. Representative Energy System for the examples of a) "Utopia" adapted from (Howells et al., 2011); and, b) "Simplicity" example (ICTP, 2018a; Taliotis et al., 2019). The diagrams describe the conceptualisation of the energy systems to be mathematically represented in an optimisation problem that OSeMOSYS will solve.

generation infrastructure, transmission and distribution). In CLEWs assessments, a similar diagram is built encompassing the systems of Land, Water and Climate systems. CLEW systems are linked via the use or conversion of commodities (also illustrated using lines). The integrated systems diagram, named here as Reference CLEWs diagram (RCLEWs), is a result of the "Pre-nexus Assessment" step in a CLEWs analysis (Ramos et al., 2021a), where systems' interactions are mapped. This mapping exercise is frequently done in collaboration with stakeholders.

To represent the interactions between systems adequately, we need to understand how the resource systems operate and are structured. Following a similar process to the RES in Fig. 1, we can elaborate diagrams for the Water and Land systems[3], presented in Fig. 2. Information about system characterisation for building the integrated systems' diagram is available in several sources (Martinez-Hernandez et al., 2017; Ramos et al., 2019; Rasul, 2016; Vinca et al., 2021) and also on cross-systems interactions (Flammini et al., 2014; Hoff, 2011; Howells et al., 2013; Laspidou et al., 2017; Ramos et al., 2021a; Skaggs et al., 2012; Sridharan et al., 2018).

The Water System, illustrated in Fig. 2a, considers precipitation and seawater as resources (represented to the left), while potable water consumption and water for irrigation are uses. Technologies for water pumping, collection, treatment and purification represent the transformation processes. While distribution technologies, which refer to water supply systems (e.g. canals, or pipelines), ensure the supply of different user types.

As for the Land system (Fig. 2b), available land is considered the resource (left-hand side). This element determines the system's boundaries by specifying the land available to the different land uses. Uses (right-hand side) refer to wood consumption, agricultural products, ecosystems, and infrastructure demands. The transformation processes depend on the activities considered, e.g. managed forests, crop cultivation, or livestock grazing.

The adopted resources-to-use approach aligns with an engineering perspective. However, aspects related to social, economic and ecological systems can be directly or indirectly introduced via model design, assumptions in input data, and scenario design. For example, demands projections can consider socio-economic parameters, e.g. population, urbanisation, and/or gross domestic product. From the model design perspective, demands can be disaggregated to represent different user categories (e.g. domestic water consumption can be defined according to settlement type and water access level). Ecological systems considerations can be made by limiting resource use (e.g. constraining forest land use to represent protected areas or surface water use to depict environmental flows). Model regionalisation is another way to characterise relevant social, economic, and ecological systems properties. In this type of modelling approach, scenario design would be a suitable method for examining the influence of socio-economic drivers. Additionally, the involvement of local stakeholders in the model design can support context-adequate model development for Nexus relevant insights.

Essential in the representation of systems are the boundary definitions and scales convergence. They assist with data requirements, give guidance on systems coverage, and put insights into perspective (i.e. what it can or not inform about). Water and Land systems are bound to geography and topography. The consistent pairing of systems scales is a frequently identified challenge (Bijl et al., 2018; Khan et al., 2017; McCarl et al., 2017; Vinca et al., 2021). Data availability for the multi-system representation influences boundaries definition, a process that should involve stakeholders. Open datasets can be used to cover data gaps. Else, the analytical approach design and assumptions can contribute to alleviating the challenge. For addressing the challenge of cross-sectoral data harmonisation, Khan et al. (2020) developed an open-source tool to reconcile such data according to user-defined scales.

2.2. Using OSeMOSYS for CLEWs modelling

OSeMOSYS is an open-source linear optimisation model generator, with various linear programming (LP) languages implementations[4], initially tailored for long term energy systems analysis. It has been used in multiple studies since its release in 2011[5]. Linear optimisation cost-minimisation models inform the technological mix and investments

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[3] Climate is included in the Water system diagram as "precipitation", and emissions are accounted for in activities in the Land, Energy and Water systems.

[4] OSeMOSYS code versions are available in GNU MathProg, GAMS and python, and can be accessed at https://github.com/OSeMOSYS/OSeMOSYS.

[5] OSeMOSYS applications span national (Dhakouani et al., 2017; Godinez et al., 2020; Pappis et al., 2021; Peña Balderrama et al., 2018; Saadeh et al., 2020; Taliotis et al., 2017), continental (de Moura et al., 2018; Henke, 2021; Sridharan et al., 2019a; Taliotis et al., 2016b), and global scales (Beltramo et al., 2021; Taliotis et al., 2016a; United Nations, 2014).

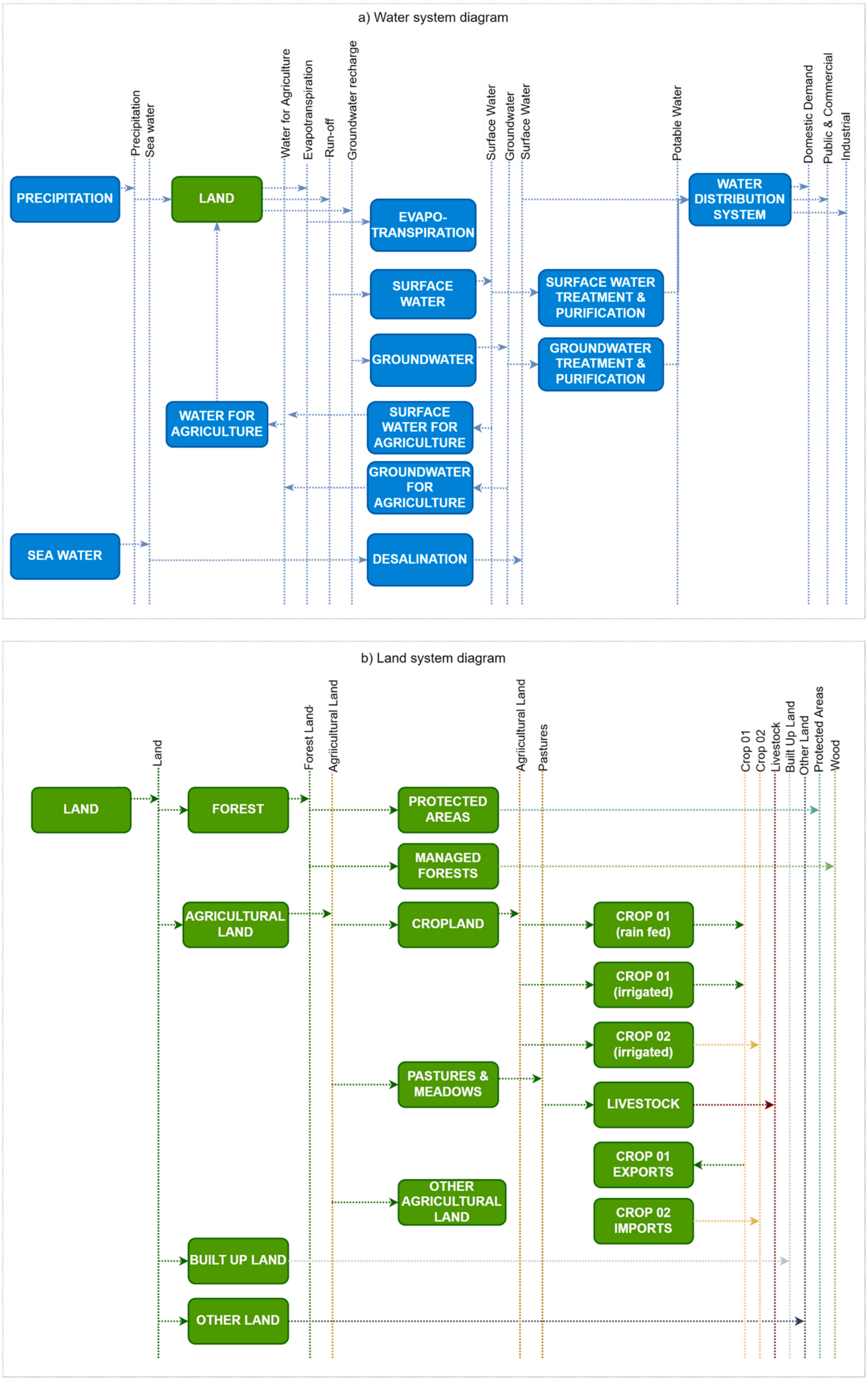

Fig. 2. Resources-to-use example illustration of the a) Water and b) Land systems. The diagrams illustrate the interpretation of Water and Land systems from a resources-to-use perspective. This is comparable to the energy system typically represented in a Reference Energy System, seen in Fig. 1. The direction of the arrows expresses the way commodities flow. In the Water system diagram, surface and groundwater generated from water-land interactions (i.e. water balance) are made available for agriculture in a separate process (e.g. "surface water for agriculture" and "groundwater for agriculture").

corresponding to the system's least-cost configuration. The solution is dependent on the technical options considered and the user-defined constraints that meet exogenously defined demands. The modelling structure is informed by the reference diagram discussed in the previous section. Examples of elements in an OSeMOSYS-CLEWs model, assuming a resources-to-use perspective, are provided in Table 1.

OSeMOSYS has been applied in CLEWs analyses differing in spatial scale, sectoral detail, socio-economic and Nexus contexts. Its single-model format application adapts to the specificities of case studies by adjusting to data availability, enabling customised regionalisation, modelling structure, and representing diverse systems elements. This versatility motivates the selection of the tool for building the integrated modelling exercise. Additionally, the tool is open source, which enables adding code functionalities for improved systems representation and easy testing. The mathematical formulation is straightforward and described in different layers of complexity, with a plain English description, algebraic formulation, and code translation, which encourages, even more, the customisation by non-experts. Plus, additional

Table 1
Overview of elements in a CLEWs representation in OSeMOSYS.

System	Resources	Conversion technologies (and/or processes)	Transmission and Distribution; supply options	Exogenous Requirements (e.g. Demands, Emissions)
Climate	Precipitation[a], climatic zones.	Not applicable (N/A)	N/A	Emission Limits
Land	Land, land with different suitability.	Forestry activities, Agriculture (crop cultivation & livestock), protected areas /ecosystems, food production systems.	Transportation of goods.	Demand for agricultural products (crops, livestock), wood products, food, etc.
Energy	Coal, natural gas, oil.	Refinery, Power plants, etc.	Grid network, stand-alone generation infrastructure.	Electricity, Demands for transportation /mobility (passenger-km), energy services (e.g. lighting, heating, cooking)
Water	Precipitation[a], Surface water, groundwater, seawater.	Water treatment and purification, water collection, wastewater treatment and disposal, run-off & groundwater recharge. Unconventional (water reuse, rainwater harvesting).	(Non-potable and potable) water distribution infrastructure, wastewater collection and distribution, storm water collection.	Agricultural water demands, non-agricultural water demands (domestic, public, industrial. commercial), environmental flows.

[a] Precipitation is a climate variable and a water system element and is considered to be part of both the “Climate” and “Water” systems.

software required for running OSeMOSYS (e.g. model management interfaces and solvers) is also open, hence without incurring costs for the user. Finally, the tool is now used by a vast community of developers, trainers, teachers, students and practitioners, who support each other through an online “Question & Answer” forum, enabling mutual and overflowing learning. OSeMOSYS benefits from having a community of practitioners (users and developers) that continuously expands its applications and support its development (Gardumi et al., 2018; Niet et al., 2021). Moreover, both the CLEWs approach and modelling tool are used in capacity development, strengthening the rationale for developing additional literature to support its dissemination and knowledge transfer. Such knowledge can be used either to expand the methodology or to understand other nexus tools.

2.2.1. Sets, parameters, variables and constraints by system

As a linear optimisation model, OSeMOSYS model code is constituted by the declarations of model objects (i.e. sets, parameters, variables, constraints and the objective function), populated and solved based on the data file of a specific problem. In OSeMOSYS, the objective function determines the least-cost configuration of technologies and resources to supply exogenous demands over the modelling period and these are defined for commodities of land, water, and energy systems.

Sets are model objects used to define the global constituents of the model. In OSeMOSYS, there are 11 set types, seven of which were used in the exercise. Their description and use are explained in Table 2.

Parameters are elements used to characterise the functioning of technologies and the demands that will drive the model. Technologies (depicted as boxes in the RCLEWs diagram) represent commodity conversion processes or can also serve to account for commodities’ use. For example, a crop cultivation process is different from electricity generation in a power plant. However, these two processes can be represented with the same parameters. A summary of parameters’ use across CLEW systems is presented in Annex D in SI. Defining the units that will be used in the model is an essential aspect of model development, particularly when different systems are characterised via the same parameters.

Variables are model objects calculated from a linear expression and can be retrieved as model outputs. Similarly to “parameters”, the same “variable” may have different meanings and units in other systems[6]. Take the example of a crop cultivation technology and a power plant. The results of the variable “Production by Technology Annual” results would be given in a multiple of the unit “tonne”, considering the crop output, in the land technology, and “petajoule” in the power plant technology. An explanation of the common interpretation of variables from different CLEWs systems, as modelled in the exercise, is provided in Annex E in SI.

Although various variables exist, a few are used for reporting. Common variables reported referring to “capacity” include “New Capacity” and “Total Annual Capacity”. For activity, “Total Annual Production by Technology” for technology outputs of a certain commodity in a year, and/or “Use by Technology” for commodity inputs in a given year. The total emissions by emission type are obtained with “Annual Emissions” or by technology with “Annual Emissions by Technology”. If an emission penalty is implemented, the total discounted costs of the penalty are retrieved in “Discounted Technology Emissions Penalty”. Costs are another group of variables often checked and retrieved as discounted or undiscounted. Regarding the costs’ variables, we recommend the use of “Discounted Capital Investment”, “Discounted Fixed Cost”, and “Discounted Variable Cost” for the costs breakdown per technology, or the aggregated version in “Total Discounted Cost per Technology”. The “Model Period Cost by Region” corresponds to the sum of the previous variable of all the technologies in all years of the modelling period.

Constraints are model objects used to set bounds to the linear problem and objective function. They define the relationship between parameter values and computed variables. Bounds can be applied to variables directly, e.g. natural gas reserves available in one year that a gas extraction technology can deploy.

Units must be coherent across systems in the preparation of model data inputs. Appropriate units can prevent scalability problems of the matrix generated when solving the LP problem. One challenge in units definition is the magnitude of the quantities represented: model inputs need to be in comparable scales. For example, in describing a national level electricity system, using the unit of installed capacity of gigawatt (GW) is appropriate, and megawatt or kilowatt could suffice for a smaller system (e.g., a rural community). Similar reasoning would be applied to water systems, for example, in the definition of demand. Billion cubic metres (BCM) could be appropriate at a national level. In contrast, at a smaller level (again, considering the number of users), million cubic metres (MCM) would provide a more direct perception of the magnitude of the demand (e.g. annual demand 1.5 MCM, versus 0.0015 BCM). The units considered in selected technologies of the CLEWs exercise are presented in Annex F in SI, and other units use examples.

2.3. Narrative and structure of the OSeMOSYS-CLEWS modelling example

The OSeMOSYS-CLEWs modelling example demonstrates how different systems can be represented in a single-model framework at the national level. It accounts multi-resources use and retrieves the technological mix to meet exogenous demands (IAEA, 2009). The example takes inspiration from previous exercises used for teaching OSeMOSYS and

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[6] For example, plotting results of the variable “Production by Technology Annual”, which informs on the commodities produced by a technology in a given year, for technologies from different systems (or even the same system) could prove difficult to arrive at any insight as we will be dealing with different dimensions (hence, units) and magnitudes.

Table 2
Overview of sets in OSeMOSYS used in the CLEWs modelling exercise (adapted from (KTH-dESA, 2018).

Set	Description	Use
Region [r]	Defines the region to be modelled, for which supply-demand balances for all the energy vectors are ensured.	Typically one region is considered, which can be disaggregated in sub-regions using other sets (e.g. technologies specific to a sub-region).
Year [y]	It represents the time frame of the model, it contains all the years to be considered in the study.	Any period of consecutive years can be considered, although the modelling approach is preferably used for medium to long-term analysis (i.e. from 1 to 2 decades to >2 decades, respectively). To avoid knife-edge effects, it is advised to extend the modelling period by 5 – 10 years.
Timeslices [l]	Represent the number of partitions a year is split on.	Times slices are defined based on the temporal variation of demands (e.g. electricity consumption profile) and/or processes (e.g. hydropower production). They are usually aggregated (e.g. 2 seasons, with 1 day type and 2 day parts resulting in 4 time slices). In CLEWs modelling, the seasonality needs to factor in the temporal variation of resources and demand across systems.
Fuel (or Commodity) [f]	Represents vectors that serve as outputs (and inputs) of technologies.	They can be aggregated groups, individual flows or artificially separated, depending on the requirements of the analysis.
Technology [t]	It includes any element of the energy system that changes input commodity(ies) to another.	Technologies represent processes that supply or convert commodities, which can be used by another technology or supply a demand. Often, they required techno-economic characterisation. Alternatively, they can be created for intermediate accounting of commodities' use.
Mode of Operation [m]	It defines the number of modes of operation that a technology can operate on.	If a technology can have one or various input or output commodities under one mode of operation or represented to operate in different ways (modes). That is the case of a cogeneration power plant that may produce heat in one mode of operation and electricity in another.
Emission [e]	Defines the emissions (or accounting elements) available to be assigned to technologies.	Emissions (or accounting elements) are assigned to specific technologies in which accounting is relevant for the analysis and proportional to their activity. This is the case of assigning greenhouse gases (GHG) emissions to fuel or livestock land technologies. This set does not necessarily need to represent emissions and can be used, for example, to account for the use of water by a power plant.

CLEWs. These include the CLEWs modelling exercise (Alfstad et al., 2016; Alfstad and UNDESA, 2016) of Mauritius[7], and the energy system-focused examples of *UTOPIA* (Howells et al., 2011; Lavigne, 2017); *Atlantis* (UNDESA, 2016); and *Simplicity*[8] (ICTP, 2018a; Taliotis et al., 2019).

The example is fictional, although assumptions are within the range of "real" conditions. It serves the objective of investigating the interdependencies between the systems of land, energy and water and their interactions with climate in the context of a hypothetical national case. The case narrative, in Box 1 [9], supported the model development (e.g. assumptions, structure and scenarios) and assisted the interpretation of the approach by offering a complementary textual description to the RCLEWs diagram in Fig. 3. Model data, including assumptions, are available in a Zenodo repository (Ramos et al., 2021b). Generic data can be used to develop similar modelling exercises. Publicly available sources are listed in Supplementary Information (SI) (Annex B). The modelling exercise was run with an adaptation of the OSeMOSYS code version of 2019[10], available at GitHub (OSeMOSYS Community, 2019), and solved with the freeware GLPK (Free Software Foundation (FSF), 2012), as described in the OSeMOSYS manual (KTH-dESA, 2018).

The example can be advanced in detail and complexity. For instance, the model is restricted to national boundaries and does not account for the trade of commodities, demands are aggregated, and the discount rate is the same for all sectors. The climate system is not represented dynamically but through an annual stock of precipitation, and emissions accounting depending on technology type. The energy system focuses mostly on the electricity sector, water availability in the water system is dependent on annual renewable water resources, a limited set of land cover types are considered, and livestock GHG emissions refer to manure management. An overview of limitations is presented in the SI (Annex C). Although it is a single model, it can support inputs from sector-specific tools, creating inter and cross-disciplinary collaboration and co-development opportunities. The OSeMOSYS code can also be updated and tailored to the analysis at hand.

2.4. Representing interactions: technology inputs and outputs

Key systems interactions are represented in the RCLEWs modelling exercise and identified in the RCLEWs diagram (Fig. 3) with dotted lines. An overview of the nexus interactions is described in continuation, starting with interlinkages (i.e. interactions between systems). Water is required for agriculture and electricity production and the supply of residential, commercial, and industrial demands. Energy is used to power water supply systems to all sectors and is an input to the land system for crop cultivation. Biomass, an energy resource originating in the land system, is used for cooking (i.e. fuelwood) and electricity generation (i.e. bagasse). Water balance components link the systems of climate, land and water. This process enables water availability for water uses in the country. Also distinctive are intralinkages (interactions occurring within the same system) in the land system. This is the case of activities that compete for the same and limited resource of land. The extent of each land use is determined by the total land available, which will not expand beyond the country's territorial boundaries. GHG emissions, although not comprehensively incorporated, are considered in all systems. Emissions of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and corresponding $CO_{2,eq}$, are represented for the uses of fossil fuels (i.e. diesel, gasoline, and natural gas), biomass burning (wood, bagasse, and crop residues), and manure left on the land. CO_2 absorption is represented for forests.

Interactions in the CLEWs model are represented via inputs and outputs (commodities' ratios) to/from technologies using the parameters "Input Activity Ratio" and "Output Activity Ratio", respectively. The conceptual approach is illustrated in Fig. 4 for the example of irrigated sugarcane cultivation, a cropland technology that requires land, water, gasoline and diesel as inputs (left) to produce sugar cane, water balance outputs (right). The values considered as inputs and outputs are relative to one activity unit of the technology, and the activity corresponds to land used for cultivating sugarcane under irrigation. This means that if one wants to represent sugarcane cultivation with different productivity, the inputs and outputs of water and energy ratios need to be updated to reflect the new land productivity. A particular case is transmission technologies (i.e. water distribution, water for agriculture, electricity transmission and distribution).

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[7] This example has been used for the overall dissemination of the CLEWs approach and to promote the importance of the integrated approach in policy design since its release in 2016 (Alfstad and UNDESA, 2016).

[8] The *Simplicity* example includes selected CLEWs elements, and its reference diagram is available in Annex A in SI.

[9] "Policy direction" refers to the medium and longer term vision shaping the country's strategic planning processes. These can include, for example, the aim of decarbonising the economy, reducing energy dependency, adhering to international agendas (e.g. Paris Agreement), or protecting the environment.

[10] Minor changes were implemented to the code in order for emissions, and variable and operating costs to accommodate negative values. The model code can be accessed in the Zenodo repository (Ramos et al., 2021b).

Box 1
Narrative of the hypothetical CLEWs national case that guided model development. Detailed trends and assumptions are presented in the supplementary material.

In 2020, six million inhabitants lived in the country, half of which in cities. The population is expected to grow, on average, 2% annually, reaching 11 million in 2050, and the urbanisation rate by 1% every year. All inhabitants have access to electricity, drinking water, and sufficient food and nutrition. Electricity and water consumption is mainly driven by population growth and urbanisation, while the demand for agricultural goods is linked to economic trends.

The country aims to improve access to commodities through the sustainable and efficient use of resources in terms of policy direction. Planning and sectoral institutions are increasingly interested in implementing integrated planning approaches. The government follows international agendas, such as the Nationally Determined Contributions, decarbonisation and Sustainable Development Goals.

The climate is sub-tropical, and the average precipitation is 2275 mm/year. Uncertainty exists regarding the future climate, which can be wetter or drier than historical trends. With a total land area of 150,000 km^2, forests dominate the landscape (35%, 57% of which is protected primary forest), followed by agricultural land (25%). Built-up land covers 5% of the territory and corresponds to infrastructure for settlements, road networks, and industry. Forest stocks are estimated at 150 tonnes of wood per hectare, and wood production is estimated at 20% of the forest stock. Agricultural activities cover most of the national food demand, with the livestock sector and the production of maize and sugarcane being significantly expressive. Agricultural output is expected to increase by 25% every decade. The use of irrigation systems is less common than rain-fed crop cultivation, and mechanisation (diesel and gasoline use) is higher where there is deployment of irrigation schemes.

Energy is needed for cooking, electrical appliances, transportation, and a requirement for agricultural activities. Wood, a product from forests, is used for cooking at the household level at an annual rate of 35 kg per capita. Factoring in other wood uses for energy purposes (e.g. manufacturing, pulp and paper, and other industries), the annual per capita is estimated at 109 kg. A combination of technologies produces electricity: thermal power plants fuelled by diesel, natural gas and biomass (sugarcane bagasse); and renewables, like run-off-river hydropower plants, solar photovoltaic and wind power. In thermal power plants, water is used for cooling systems. Cooling towers are used in gas power plants, while diesel and biomass operate with run-through cooling systems. The country relies on diesel and gasoline imports, while natural gas reserves limit its extraction to 200PJ annually. Bagasse, a by-product of sugarcane crushing, is used for electricity generation. Annual electricity consumption by inhabitants in urban corresponds to 4000 kWh, while consumption is lower in rural areas, at 2000 kWh/year. For urban users, electricity consumption is expected to increase by 500kWh/year every decade; by 2050, the electricity use will be equal for all users at 5500 kWh/year.

Water availability is largely dependent on precipitation patterns. Thus the majority of water is collected from surface water sources. All water resources are internally generated, thus not traded across political boundaries. Aquifers are sparse and not considered cost-competitive water sources. All inhabitants have access to safe drinking water sources (treated water), and water is also used for public, commercial, and industrial uses. One person consumes, on average, 250 litres of water per day (Lppd), and rural consumers 75% of urban rates. Water consumption is expected to increase by 50 litres every decade for urban users, reaching a daily rate of 400 Lppd by 2050; value also planned to be attained by inhabitants in rural settlements in the same year. Water distribution systems incur significant losses, which reach 20% in residential, public and industrial supply, in the supply systems to thermal power plants, and 30% in agriculture. Water used in the agriculture and electricity sectors is not treated.

The dimensioning depends on the amount of input they can process (e.g. processing capacity). In these cases, the output of the technology should be expressed as one minus the losses so that capacity reflects the actual capacity size requirement (and investments).

2.5. Scenarios overview

Changes in resources use may be motivated by natural factors, such as changes in climate. Sometimes they are motivated by decisions that do not account for cross-systems implications. In such cases, policies and sectoral strategies can be counterproductive (Howells et al., 2013; Kling et al., 2017; Rasul, 2016; Sridharan et al., 2019a, 2019b). To illustrate the type of analyses performed with the modelling example, we examine six scenarios: a reference case, four system-specific cases, and a scenario that considers all aspects changed in the system-specific. Reference (REF) scenario general assumptions and trends are presented in Table 3, and exogenous demands are in Fig. 5.

In line with the purpose of CLEWs assessments applications developed over the last decade[11], futures investigated are influenced by policy decisions, technological transition, and resource-efficiency measures. Additionally, aspects related to climate are taken into account through changes in precipitation or by limiting GHG emissions. A summary of the measures and actions considered in the scenarios is presented in Table 4, and an extended description is available in SI (Annex G).

The proposed scenarios can be imagined from the perspective of different decision-makers. The *climate scenario* is motivated by the political ambition of decarbonisation, which translates into sectoral interventions needed to reduce GHG emissions. A decrease in rainfall due to climate change is assumed in this scenario. In the *land scenario*, more sustainable and efficient practices aim to transform the agricultural sector. This ambition is defined by limits to land use by agriculture from the governmental level. As an example of diversification of land use activities, reforestation projects are introduced with benefits from ecosystems services. In the *energy scenario*, the electricity sector prepares for a demand increase driven by population growth and increasing consumption rates, resulting in a reduction of fuelwood consumption for cooking. To promote the use of crop residues, the government sets targets for bagasse use in electricity generation. In the *water scenario*, the increase of demand by residential users is promoted by the government. In response to the increased supply requirement, the water supply sector introduces water efficiency measures. The *integration (or combination) scenario* joins all the above ambitions and sectoral actions.

3. Insights and application

In an integrated analysis, questions can be asked from sectoral and

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[11] The purpose of CLEWs studies focused on one or more of the following themes: policy (coherence and impact), technology deployment and transition; resource management and efficiency; international cooperation and collaboration; climate studies; and other (Ramos et al., 2021a).

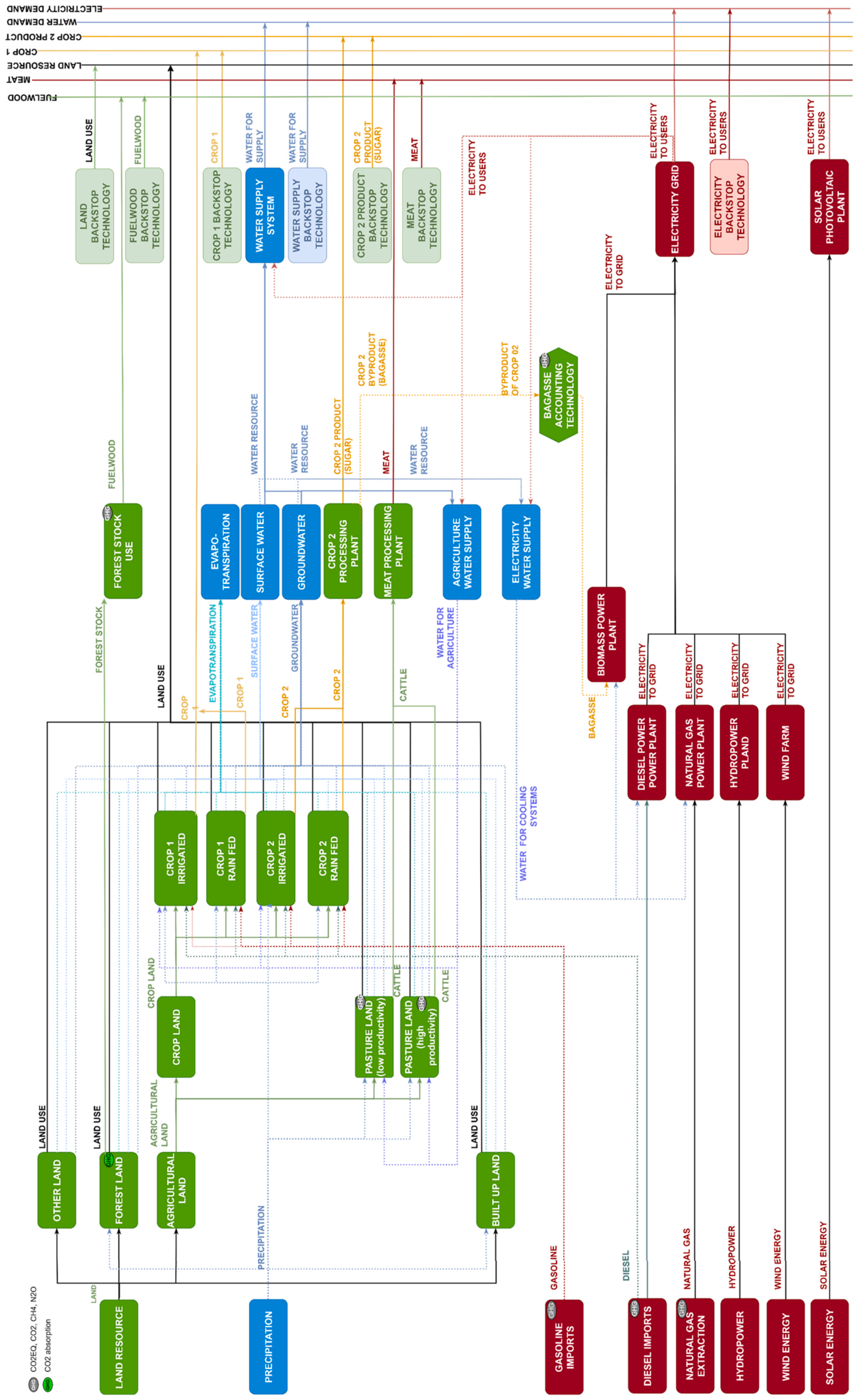

Fig. 3. Reference CLEWs diagram (RCLEWs). The diagram illustrates how the CLEW systems are represented in the OSeMOSYS-CLEWs modelling exercise. Boxes represent processes while lines are input and output commodities. The colours red, green and blue identify the system represented, respectively, Energy, Land and Water. The climate system representation is embedded in solar and wind energy potentials and in the process representing "precipitation". Dotted lines depict cross-system interactions and illustrate when commodities are used across systems. Backstop technologies, with outputs corresponding to the demand commodities, are added to the diagram and included in the model structure to facilitate model debugging. These technologies have very high costs (capital, fixed and variable) and will only contribute to meeting demands if there are inconsistencies or errors in the upstream chains that lead to the generation of the demand commodities. Other backstop technologies can be introduced throughout the model structure, not only before demand, functioning as checkpoints for upstream chains of technologies and commodities.

integrated viewpoints. Model findings, defined by the mathematical representation performed, can inform at both these levels. While modelling results illustrate how the quantitative method reports about a specific Nexus context, it is also important to discuss how they can be communicated. This section presents types of insights derived from the modelling example, describes how it can be used by practitioners, and explores how the example can service knowledge transfer (and learning) of the Nexus approach among different audiences, thus supporting the approach's adoption.

Although not considered in the example presented, the authors recognise the importance of including sensitivity and uncertainty analyses in the modelling approach discussed in this paper. Yet to be systematically included in OSeMOSYS-CLEWs applications, examples of these types of analyses exist, particularly in energy system studies. For instance, sensitivity analysis in OSeMOSYS applications was performed through scenario analysis from changing input data of specific parameters (e.g. techno-economic, commodity prices, discount rate, etc.) in the study of Egypt's power sector (Rady et al., 2018), in the investigation rooftop PV penetration and gas market prices implications to generation expansion planning (Nunes et al., 2015), and in the study of Ghanaian

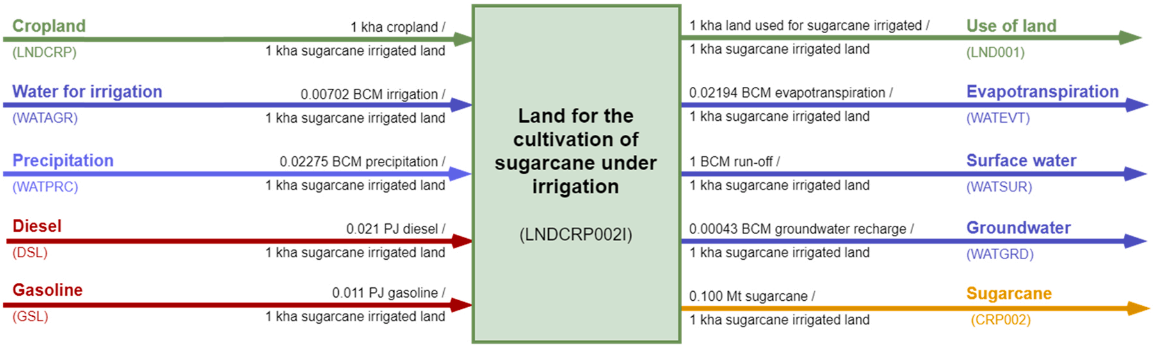

Fig. 4. Illustration of inputs and outputs, in the same mode of operation, in a cropland technology. Units in the figure correspond to: BCM - billion cubic metres, kha – thousand hectares, and Mt – million tonnes. Model name codes for the land technology (i.e. LNDCRP002I) and input and output commodities (e.g. WATAGR) are displayed in the figure for reference. A cropland technology represents an area of land of a certain crop productivity correspondent to the combination of inputs and outputs, which operate under a defined cost structure.

Table 3
Overview of general assumptions in the hypothetical national case in the Reference scenario. The complete list of assumptions and model data is available in (Ramos et al., 2021b).

Category	Variable	2020 value and trends in the Reference scenario
Demographics	Population	6,000,000 inhabitants
	– Average annual growth rate	2%
	– Urban (% total)	50% (2020)
	– Rural (% total)	50% (2020)
	– Urbanisation rate	1%
Economic	GDP growth rate (%)	2%
Climate	Precipitation	2275 mm/year
Energy	Electricity consumption	
	– Urban	4000 kWh/capita/year (500 kWh increase per decade)
	– Rural	2000 kWh/capita/year (increase to 5500 kWh/capita in 2050)
	Fuelwood consumption	35 kg/capita
Water	Domestic water consumption	
	– Urban	250 Lppd (increase by 50 litres/ decade for urban users)
	– Rural	75% of urban consumers (increase to 400Lppd by 2050)
	Water system losses	30% in agriculture; 20% in all other supply systems
Land	Total Land	150,000 km^2
	– Forest land	35% (20% primary)
	– Agricultural land	25%
	– Built-up Land	5%
	Agriculture Sector	
	– Maize (area rain-fed/ irrigated)	100 kha / 14 kha
	– Sugarcane (area rain-fed/ irrigated)	92 kha / 18 kha
	– Livestock system (area / cattle intensity)	3587 kha / 1.32 cattle heads ha^{-1}

electricity system pathways (Awopone et al., 2017). In the presence of deep uncertainty, Moksnes et al. (2019) use scenario-discovery (Bryant and Lempert, 2010) to investigate determinants of energy futures in the South American Model Base (SAMBA) OSeMOSYS model (de Moura et al., 2018). Dreier and Howells (2019) develop a framework that integrates Monte Carlo simulation in OSeMOSYS (i.e. OSeMOSYS-PuLP[12]) to analyse exogenous uncertainties of modelling parameters on model outputs by considering real-world public transport data. In integrated assessments, Peña Balderrama et al. (2020) perform a sensitivity analysis of international commodity prices in the OSeMOSYS-CLEWs model of Bolivia. Under conditions of deep uncertainty, Robust Decision Making was used in the evaluation of climate resilience of electricity sector infrastructure in seven major African river basins to account for uncertainty of climate projections (Cervigni et al., 2016; Sridharan et al., 2019a, 2019b).

3.1. *System-specific and integrated insights*

An overview of scenario results is provided in this section, emphasising sectoral and cross-sectoral trends, including the sectoral and cross-sectoral implications of increasing exogenous demands (e.g. crops and livestock, electricity and water) or the impact of activity limits. Selected results for the Reference (REF) scenario are summarised in Fig. 6, providing an overview per CLEW system over the “reference” future and of cross-system dynamics. System-specific REF scenario results are shown in Fig. 7. While the reference case provides a baseline for the comparison of alternative futures, practitioners should understand the trends emerging from the case results and ponder their plausibility. Such an analysis process may result in the revision of model structure or assumptions. The simplified model presented captures critical (yet basic) dynamics between systems. When building real-case (not hypothetical) exercises starting from this example, future users should compare their results with existing data for calibration of initial-years trends and define assumptions aligned with current practices and foreseen trends. In the REF scenario results, the investment in rain-fed sugarcane cultivation in 2039, after the predominant contribution of irrigated cropland for meeting sugar production targets, is an example of the importance of understanding the model’s dynamics. Cropland technologies are considered to have an operational life of 15 years. This assumption allows for a rain-fed production system to expand using freed-up land from irrigated cultivation 15 years after it was invested on. In that specific year, the least-cost solution indicated that producing sugarcane from rain-fed cultivation was cost-effective, even though such change would realistically be made. Results of this kind can be observed when there are limited options for the production of commodities: the choice, in this case, was between two distinct production systems, one more expensive that requires irrigation but with double the productivity.

The scenario comparison informs about cross-sectoral implications derived by single-sector measures, while the integration scenario informs on dynamics of cross-sectoral planning. Such types of analyses can assist the identification of sectoral level spillovers induced on other systems. In Table 5, we present an overview of selected results and their implications by system. More specifically, we compare results in terms of electricity generation, land use, water supply requirement, and

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[12] The modelling framework OSeMOSYS-PuLP is openly available and can be accessed at: https://github.com/OSeMOSYS/OSeMOSYS_PuLP

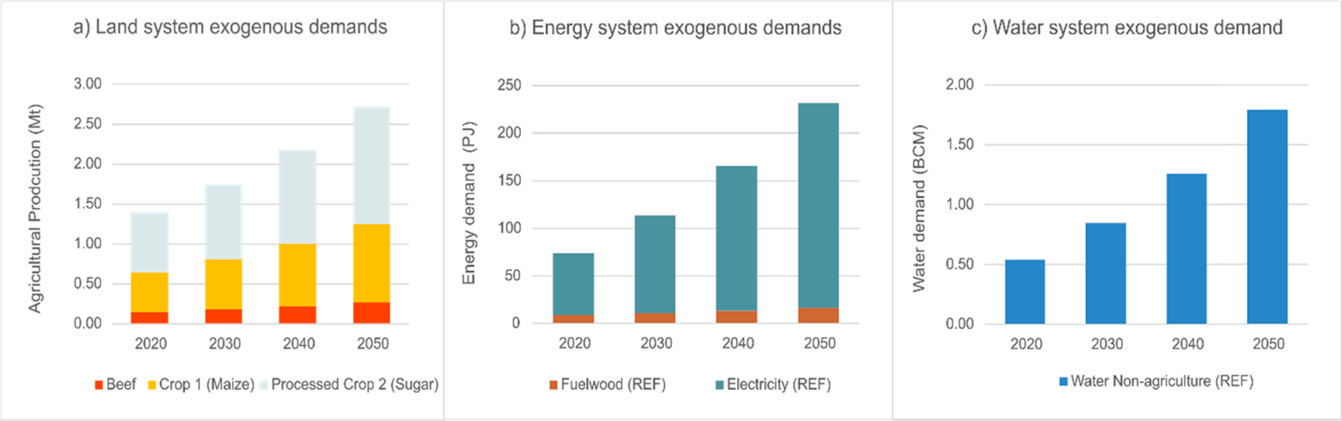

Fig. 5. Exogenous demands considered in the model for the a) land, b) energy, and c) water systems in the Reference (REF) scenario. Processes outputs are driven by exogenous demands. The charts show the demands considered and how they evolve throughout the modelling period.

emissions (Fig. 8), in terms of cross-sectoral resource use (Fig. 9a-k), and total costs (Fig. 9l). We note these are results for the CLEW system represented and respond to the assumptions, constraints, and data used. Additional results are reported in SI (Annex H).

The scenario analysis allowed the identification of implications across systems of several policies and sectoral measures in combination. Key insights, in terms of conflicts, trade-offs, opportunities and synergies, are summarised in Fig. 10, and illustrate the type of outputs the modelling exercise could provide to policy and planning processes. Assuming the quantification method was developed for a specific case, such types of outputs could motivate the development of further analyses or inform the elaboration of sectoral strategies and plans.

Table 4
Overview of scenarios explored with the OSeMOSYS-CLEWs exercise and parameters affected in the model implementation. We recommend readers to support the interpretation of the table with the RCLEWs diagram in the excel file in the Zenodo repository.

Scenario	Summary of measures and changes to trends		
	Natural systems & resource availability	Sectoral actions	Policy measures
Climate (CLM)	Annual variation of precipitation.	Improved practices in the livestock sector (e.g. manure management).	Cap to annual $CO_{2,eq}$ emissions (neutrality).
MODEL IMPLEMENTATION:	*Reduction of precipitation in the parameter is introduced in "Total Technology Annual Activity Upper Limit" for the precipitation technology (i.e. MINPRC001). Changes to precipitation require the update of water balances inputs and outputs for land technologies that have water balance representation (e.g. "Input Activity Ratio" for precipitation, and "Output Activity Ratio" of evapotranspiration, run-off, and groundwater recharge).* *Precipitation changes affects summer water availability for hydropower, a change implemented in the hydropower technology (PWRHYD001) "Capacity Factor" for the timeslices SD and SN (summer day and night).*	*Update of "Emission Activity Ratios" of livestock technologies (starting with AGRPST001/2) and costs of the technologies ("Capital" and "Fixed" Costs).*	*Introduction of "Annual Emission Limit" of zero (0) Mt per year to the CO2EQ emission.*
Land (LND)	–	Reforestation leads to net profits of 200 USD/ha	Agricultural land must not exceed 1/3 of the total land resource.
MODEL IMPLEMENTATION:	–	*Profits in OSeMOSYS are represented using negative values. Thus, a negative "Variable Cost" is introduced in the Forest technology (LNDFOR001) converted to the units in the model (i.e. −0.200 MUSD/kha)*	*Introduction of a "Total Technology Annual Activity Upper Limit" to the agricultural land technology (LNDAGR001).*
Energy (ENR)	–	Increase of electricity demand and decrease of fuelwood consumption.	Use of all the bagasse produced for electricity generation.
MODEL IMPLEMENTATION:	–	*The changes are implemented in the "Accumulated Annual Demand" parameter for the commodities "ELC002" and "WOO", respectively representing electricity and wood demand.*	*Introduction of a "Total Technology Annual Activity Lower Limit" and "Upper Limit" for the biomass electricity generation technology (PWRBIO001) fixing the output to the maximum bagasse available, ensuring its use.*
Water (WAT)	–	Reduction of water supply system losses.	Increase of exogenous water demand (domestic, commercial and industrial).
MODEL IMPLEMENTATION:	–	*Water system losses are represented in the "Output Activity Ratio" of the water supply technologies to agriculture, electricity and public supply (i.e. WATAGR001, WATELC001, WATTRN001). For the exercise, capital costs of these technologies were not changed. Ideally they should be increased to represent the improve in efficiency.*	*The changes are implemented in the "Accumulated Annual Demand" parameter for the commodity representing the exogenous water demand "WAT002".*
Combination, (COM)	All of the above	All of the above	All of the above
MODEL IMPLEMENTATION:	*All of the above*	*All of the above*	*All of the above*

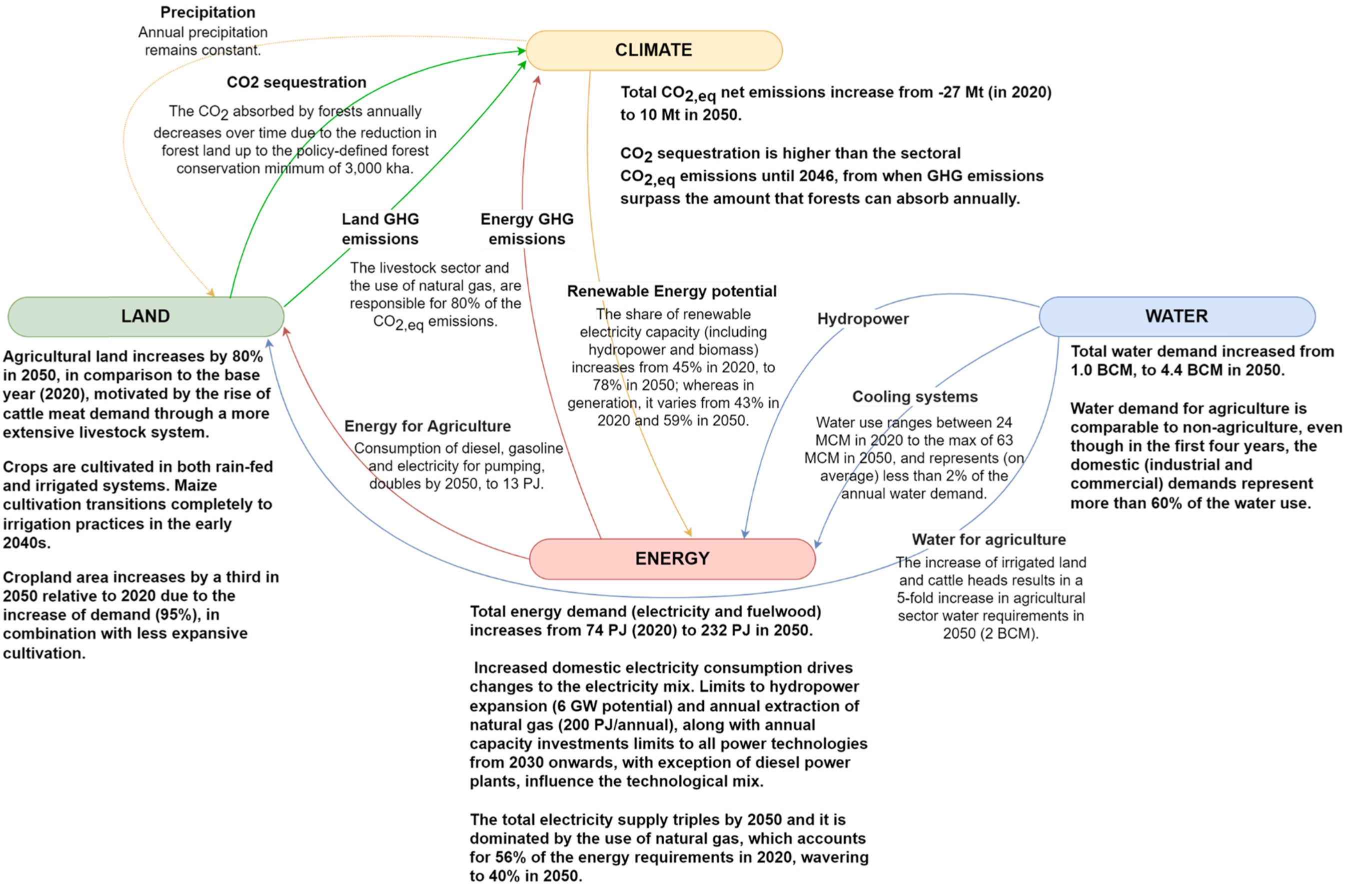

Fig. 6. Summary of system and cross-system results of the Reference Scenario. An overview of system-level results is provided under each system's label (Climate, Land, Energy and Water), indicating main trends and how the system's elements changed by the end of the modelling period. Cross- and multi systems implications are described over the interlinkages represented in the model, which are denoted by arrows.

When modelling a combination of systems, it is difficult to represent all at an equal level of detail, replicate the Nexus context, or capture particular dynamics. In a basic example, many aspects need to be simplified; however, streamlining and clarifying the approach (i.e. structure, data, assumptions, and outputs) can be valuable for non-modellers, particularly decision-makers. Simplified modelling examples can facilitate understanding models use, their scope and limitations, and elucidate on the type of questions they can explore (Saltelli et al., 2020;). The OSeMOSYS-CLEWs example can be used as an initial effort to expand to CLEWs-type assessments the u4RIA[13] principles on data management and best practices in modelling (Howells et al., 2021b).

3.2. Using the OSeMOSYS-CLEWs modelling exercise

OSeMOSYS is an open-source software whose use can be supported by open solvers and open software for pre- and post-processing. System requirements are linked to the solvers' specifications.

The process of developing the OSeMOSYS-CLEWs example is illustrated in Fig. 11 and divided into four distinct stages. These are (A) defining the context, (B) data preparation, (C) running the model, and (D) results and analysis. The first (A) refers to defining the context, developing the model structure, data collection and the definition of assumptions, for the preparation of the inputs dataset in stage B. For building model data text files, practitioners may use the open software *otoole* (Usher, 2019) pre-processing module[14] or the graphical user interfaces (GUI): Model MAnagement Interface (MoMAnI)[15] or the recently developed OSeMOSYS GUI[16]. Running the model (stage C) requires a linear optimisation solver, the input data text file and the OSeMOSYS code text file. The results (stage D) are obtained in a text file format and a set of *.csv* files, and can be visualised through the platform created for this exercise, available in the Zenodo repository, via the *otoole* post-processing package[18], or Excel.

The RCLEWs modelling exercise was run with an adaptation of the OSeMOSYS code version of 2019 (written in GNU MathProg[17] and is available in GitHub (OSeMOSYS Community, 2019)). The optimisation problem was solved with the freeware GLPK (Free Software Foundation (FSF), 2012), as described in the OSeMOSYS manual (KTH-dESA, 2018). It can also be solved with other solvers such as CBC and Gurobi.

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[13] u4RIA stands for "universally Retrievable, Repeatable, Reconstructible, Reproducible, Interoperable and Auditable".

[14] Description of *otoole* use for pre-processing: https://otoole.readthedocs.io/en/stable/functionality.html#pre-processing

[15] MoMAnI instructions are available at: http://www.osemosys.org/interfaces.html

[16] The interface developed by UNDESA can be accessed here: https://osemosys.herokuapp.com/#/

[18] *otoole*'s post-processing is described at: https://otoole.readthedocs.io/en/stable/functionality.html#results-and-post-processing

[17] The OSeMOSYS code is also available in other programming languages, such as GAMS and python (https://github.com/OSeMOSYS/OSeMOSYS).

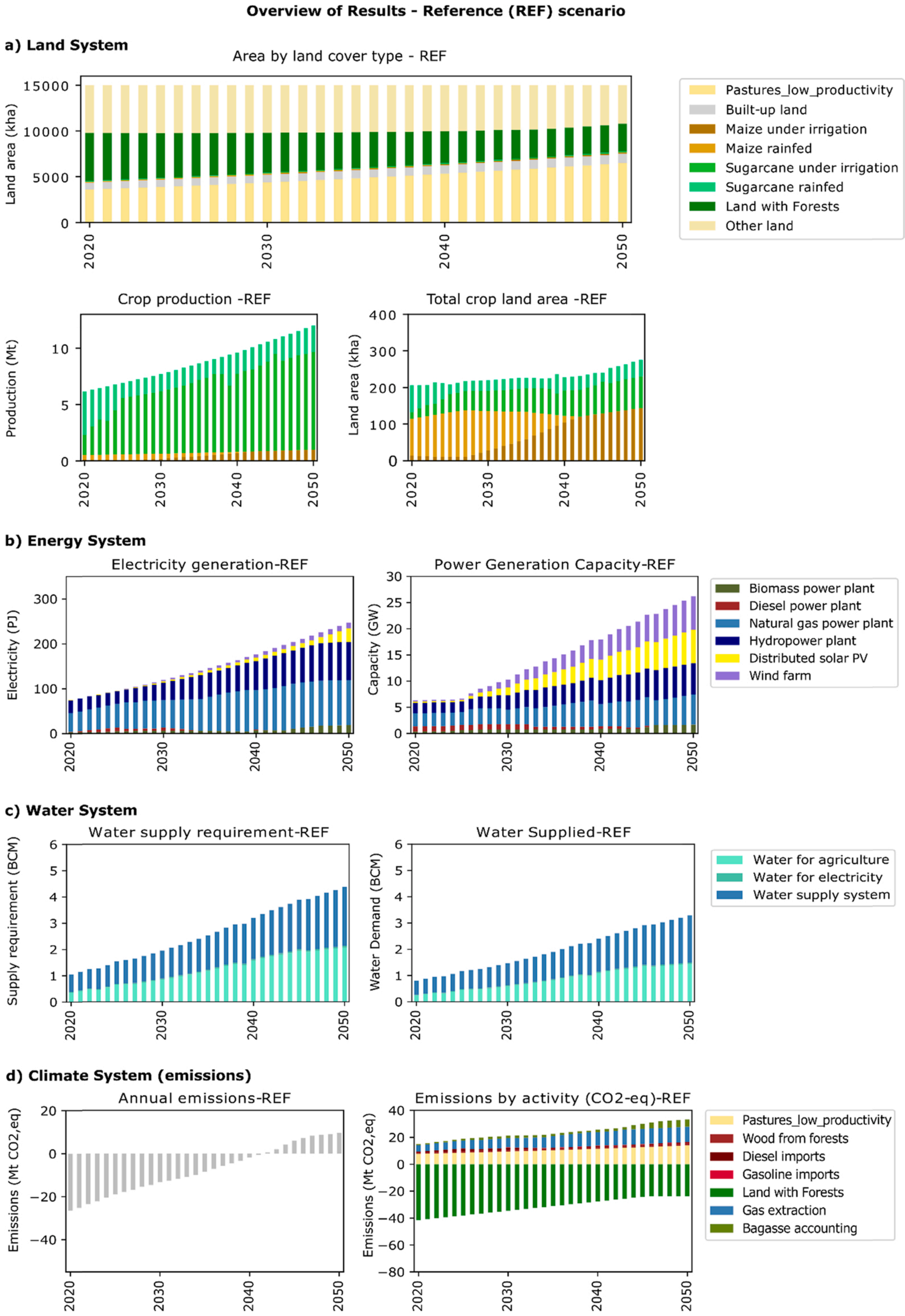

Fig. 7. Reference (REF) scenario selected results. In the "Land system" (a), the overall land use is shown in the top chart, and detail on crop production by crop-land type is given. To illustrate the "Energy system", electricity generation and the installed capacity configuration results are provided (b). The increasing demand requires the expansion of non-hydro RE, and fossil fuels are required to meet the electricity needs throughout the modelling period. Water requirement and supply for the multiple water uses are shown in the "Water system" charts (c). Results for $CO_{2,eq}$ net emissions (chart d, left) illustrate the emissions balance in the modelling period. A detail of the $CO_{2,eq}$ by process (chart d, right) provides a perspective of the contribution from the different systems.

3.3. Entry-points to integrated quantitative assessments

A cross-systems perspective in solving complex problems requires a transdisciplinary effort (Albrecht et al., 2018; Bréthaut et al., 2019; Ghodsvali et al., 2019; Wiegleb and Bruns, 2018). The management and use of resources imply the involvement of various stakeholders working at different decision levels and the inherently embedded policy dimension. Integrated analyses can seem challenging to introduce, particularly in organisational contexts less familiar with the practice. Platforms exist disseminating the growing number of nexus applications (GIZ, 2016; KTH-dESA, 2017b; Arenas et al., 2021), aiding mutual learning and policy transfer (Fritsch and Benson, 2020). Nonetheless, due to the specificity of the examples, the transfer of methods is not easily accessible. Practitioners and the Nexus community could benefit from having access to transferable methods that can be deployed regardless of the context without much prior knowledge of the tools. Benefits would be greater if methods were open, operated using open software, and supplemented with educational materials to support independent learning. This paper moves a step toward offering an accessible and transferable body of knowledge on a quantitative Nexus modelling approach that

Table 5
Insights from the comparison of scenario results.

Climate System

The net emissions balance in the REF and WAT scenarios is positive from 2042 and in the ENR scenario from 2039. Incentives to reforestation ensure a negative emissions balance in the LND and COM scenarios, in which forests replace "other land". In the CLM scenario, neutrality is reached in 2043, possibly due to increased forest cover beyond the minimum 3000 kha. In the COM scenario, $CO_{2,eq}$ emissions increase due to bagasse burning and diesel use prompted by the ENR scenario measures (i.e. increased electricity demand and use of bagasse potential), as seen inFig. 8. Still, the net emissions remain negative throughout the entire modelling period as there are incentives to expand the forest area and, thus, CO_2 absorption. This means that in an integrated case, measures in other systems (e.g. land through reforestation) can compensate for increased emissions in other sectors, also evident by the influence of LND scenario measures in the dynamics of the COM scenario (Fig. 8, Land and Climate systems charts).

Land System

Greater changes in land use are directly related to actions in land use (e.g. incentives for reforestation) or limits to the expansion of agricultural land, which force a transition to higher productivity (i.e. irrigated land, and less extensive cattle raising). For instance, the reduction of irrigated cultivation of maize is compensated by the increase in rain-fed cultivation in the ENR scenario, an expansion that requires the use of "other land" (Fig. 8). In contrast, in the two first decades of the CLM scenario, irrigated cultivation (especially maize) is preferred over rain-fed compared to the REF scenario (Fig. 8). In the last five years of the CLM scenario, part of the land used for cattle raising with low productivity is allocated to rain-fed sugarcane in the REF scenario. From 2035, in the LND and COM scenario, investments are made in higher productivity livestock systems (Fig. 8). These only show when a limit for agricultural land is defined (LND and COM scenarios).

Energy System

The increase in electricity generation in the ENR and COM scenarios is met by increased wind and diesel–based generation and the expected higher contribution from bagasse (due to the imposed minimum use equal to the bagasse available) seen inFig. 8. More electricity needs to be supplied from the grid, as there are limitations to solar photovoltaic investments. Measures introduced in the WAT and LND scenarios produce minor changes to electricity generation (see scales in the energy charts inFig. 8). Hydropower generation reduction in the CLM scenario is compensated by diesel, gas and solar technologies.

The use of all bagasse available for electricity generation is only achieved when such action is enforced - which is the case of the ENR and COM scenarios. In contrast, about 60% of the bagasse potential is exploited in the other scenarios, as seen inFig. 9.g-h. The results suggest that bagasse use targets influence land allocation for irrigated sugarcane cultivation. For example, in the ENR and COM scenarios, the share of irrigated land is more stable and around 66% (Fig. 9.i). However, this is not the case for the remainder scenarios, in which higher irrigated areas are found, and bagasse use is lower than the potential. Higher irrigated sugarcane land is found in the LND scenario due to limits to agricultural land that incentive land efficient practices and the CLM scenarios, where emissions reduction is also achieved through a decrease in bagasse burning (Fig. 8.d).

Water System

Even though domestic water demand increases in the WAT scenario (Fig. 8, water system charts, WAT and COM scenarios), energy use for water supply systems is higher in the CLM and COM scenarios (Fig. 8.c,Fig. 9.b), respectively due to a water demand increase in the agricultural sector (Fig. 9.f), and the combined effect of increased water demands. In the CLM scenario, water demand increase (for agriculture) is the most expressive of all scenarios, including the integrated scenario (Fig. 8). This is because irrigated practices are dominant over the modelling period and expand further in the CLM, particularly for maize. Extensive use of land for agriculture is possible since there are no constraints for land use, and the induced reforestation rate is enough to ensure carbon neutrality. Water use decreases gradually from the late 2020 s in the ENR scenario (Fig. 8), resulting in a 50% reduction, in cumulative terms, relative to REF. It is the future with lesser land under irrigation (40% irrigated land on average), as shown inFig. 9.k, and, consequently, the highest total cropland area. In contrast, the remainder scenarios do not deviate significantly from the REF and indicate a similar cropland area over the modelling period's last decade.

Total Costs

In terms of total model period costs (Fig. 9.l), the integrated scenario is the most expensive and 50% higher than the reference. However, the system-specific energy scenario (ENR) is significantly higher than the other system-specific scenarios, being 30% more expensive than the REF. Interventions in the land system, and changes related to the climate, show lower costs (~12%) than the reference case, and the water scenario measures are not different cost-wise. We conclude that sectoral measures do not necessarily need to translate into added costs, and their benefits to the overall system can balance out more expensive decisions.

could ultimately be developed to inform integrated systems planning. It explains how aspects from the CLEWs framework are translated into a model, and what type of analysis can be performed. Additionally, it introduces a sample and customisable teaching example exploring CLEWs dynamics. The authors and experts from international organisations have been developing and applying elements of this didactic approach to capacity development on integrated resource modelling in the past decade[19,20]. This work structures, conceptualises and documents the approach, to connect it with academic practice and make it transferable. This section explores how knowledge transfer and learning in Nexus modelling could be facilitated using the OSeMOSYS-CLEWs modelling approach.

How the OSeMOSYS-CLEWs exercise is used varies with the purpose and target audience. Table 6 lists four possible general use cases[21] of the OSeMOSYS-CLEWs example. Use cases follow a specific, although flexible, structure. This work adopted elements in (Cockburn, 2000): general use case, actors, subject-area, trigger, pre-conditions, main success scenario, and alternative paths (listed in rows in Table 6). The "general use case" is a high-level summary of the case; the primary actors are the users performing the intended behaviour; the subject area defines the area of application that includes the users' environment. Stakeholders are actors of interest that relate to the case, within which the primary actor is found. The event that initiates the use case is identified as "trigger", and requirements that must exist or events that must happen before the use case is realised are known as "pre-conditions". All the elements lead to a "main success scenario", which corresponds to the envisaged outcome if everything happens as described. If not, "alternative paths" can be used to detail eventual deviations.

The four general use cases of the OSeMOSYS-CLEWs exercise refer to its use in academia, capacity development, participatory approaches and open science. In "academia", the exercise can be included in different levels and explored at varying complexity. It can serve as an introductory example to showcase the Nexus approach in environmental sciences in undergraduate programmes, in a similar way suggested by

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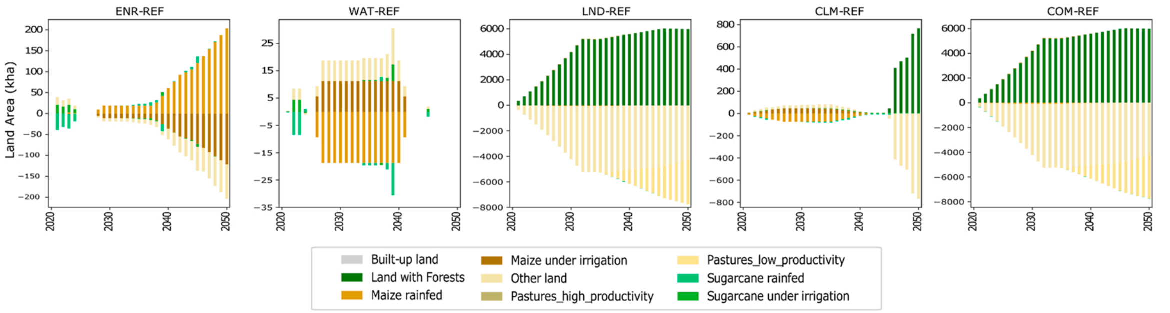
[19] OSeMOSYS has been taught in numerous country-level energy systems analysis capacity-building activities under the scope of projects organised by a variety of international organisations (e.g. Uganda, Bolivia, Nicaragua, Paraguay, and Ghana (UNDESA / UNDP, 2017), Ethiopia (Pappis et al., 2021), Costa Rica (Bataille et al., 2020; Godinez et al., 2020), Tunisia (Gardumi et al., 2021; Howells et al., 2021a), in summer schools (ICTP, 2021, 2019, 2018b, 2017; OpTIMUS Community, 2019), and is part of higher education curricula worldwide (Niet et al., 2021). In support of the previous activities, educational resources suited for curriculum integration, capacity development, or self-paced learning have been developed over the years (Allington et al., 2021; Kubulenso et al., 2019; UNDESA, 2016).

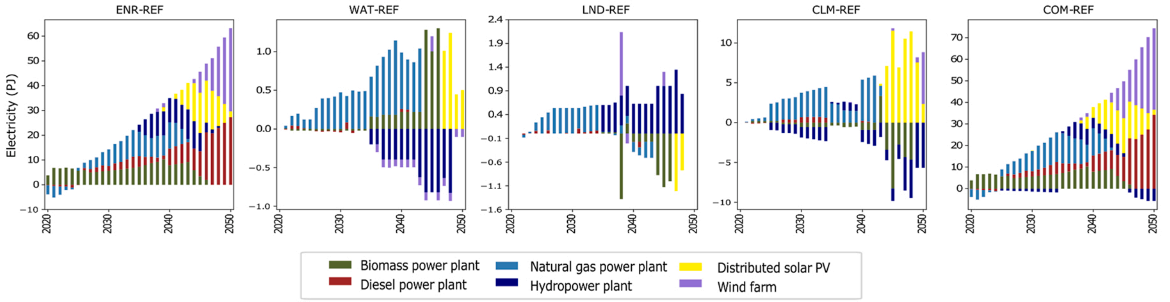
[20] Since 2017, CLEWs modelling for in-country training follows a single model approach using OSeMOSYS. The approach, led by UNDESA/UNDP and the Royal Institute of Technology (KTH), has been implemented in more than 15 countries (UNDESA / UNDP, 2017; UNDP and UNDESA, 2021). Activities are usually conducted through a series of in-country week-long workshops targeting an inter-institutional group of government officials (Alfstad, 2019; Ramos et al., 2021). Similarly to OSeMOSYS, CLEWs training and teaching enabled the development of supporting materials (Alfstad et al., 2021; Alfstad and UNDESA, 2016; OSeMOSYS/clewsy, 2021; UNDESA / UNDP, 2016).

[21] Use cases describe ways an object (or system) is utilised by a user for a certain purpose (Jacobson et al., 2011). The concept emerged in the late 1980s linked to object-oriented software development and expanded to business processes (Cockburn, 2000). In Nexus research, it has been applied in the development of Serious Games to describe users' behaviours in the selection of policy options affecting management resources management (Papadopoulou et al., 2020; Sušnik et al., 2018).

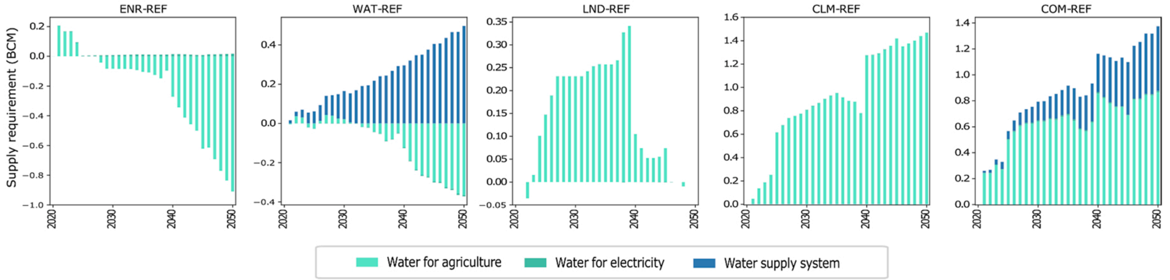
a) Land System: Use of land



b) Energy System: Electricity generation



c) Water System: Water supply requirement



d) Climate System: Emissions by activity ($CO_{2\text{-eq}}$)

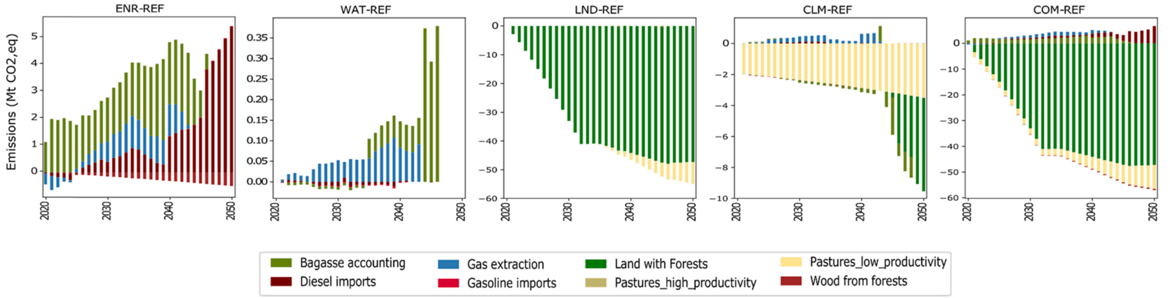


Fig. 8. Differences between scenario results and REF case, regarding: a) electricity generation; b) water supply requirement; c) use of land; and d) emissions by activity. The results show how the measures introduced in each system-specific scenario affect the different systems. In addition, it is possible to identify which set of measures (by system) exert the greatest influence on the combination scenario (rightmost column). For instance, the impact of the land-scenario measures is evident on land use (a) and climate (d) results in the combination scenario, as are the energy-scenario measures in electricity generation (first and last charts in row b). The scales of the charts vary to show the changes across scenarios, which in some cases are marginal (e.g. impact of the water and land scenario measures in electricity generation).

(Grigg, 2019) regarding the instructional use of Integrated Water Resources Management concepts. It can also be applied to new contexts at second-cycle project work (i.e. masters' level) and be expanded and advanced in third-cycle education as part of doctoral courses or research. In "capacity development", the example can be used to develop modelling capacity among technical officials. For "participatory approaches", it can be used to illustrate the type of data required for an integrated assessment and the importance of context-specific data among technical and high-level officials. It can assist in the clarification of the Nexus and sectoral terminology and inform how an analysis can be constructed and the type of insights that can be obtained. Open access to the implicated tools and methods can improve the approach and the advancement of Nexus research, transparency and transferability of methods, thus contributing to the "open science" movement.

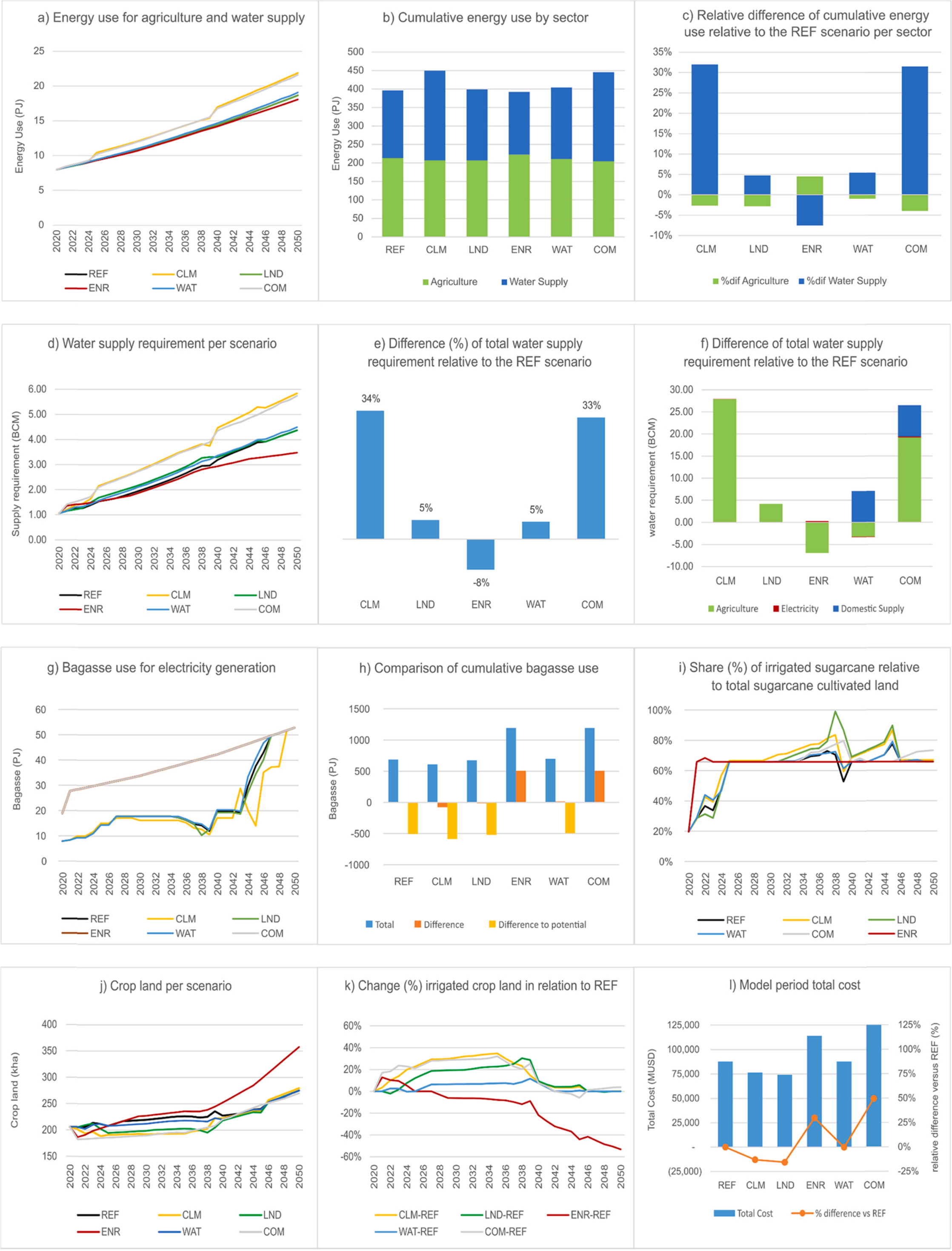
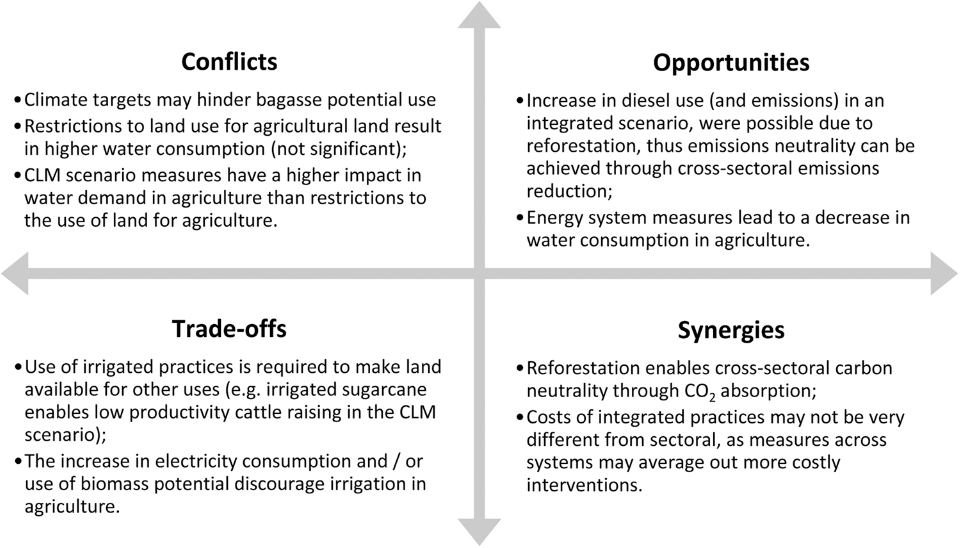


Fig. 9. Comparison of scenario results referring to cross-systems commodities use, illustrating the dynamics of systems' interactions. In the first row of charts, results are shown for energy use in agriculture and water supply annually and cumulatively in the modelling period. Total water use, and by sector, is shown in the second row. Bagasse use for electricity generation is compared across scenarios in the third row of charts, as are changes in irrigation and rain-fed sugarcane cultivation. The last set of charts shows an overview of land used for crop cultivation throughout the modelling period. Also compared is the total model period discounted cost across scenarios (chart l), indicating the expenses incurred from the implementation of the various scenario measures.

Additionally, it can promote the creation of communities of practice (CoPs) that take on the collaborative effort of applying or improving the exercise, an aspect also suggested by (Beltramo et al., 2021) regarding a global CLEWs model.

Alternatives to "use case" elements (in rows), then mapped to each general use case (columns) are listed in Table 6. The matrix can serve to create various use cases. For example, the "specific use case" of "Co-development" that, even though it can be explored in all general uses, can implicate different primary actors. "Co-development" may refer to the joint development of the integrated model by a team of students (primary actors) in the 2nd cycle; or the collaboration in model development with government officials in a CLEWs project. Take the example



Conflicts

- Climate targets may hinder bagasse potential use
- Restrictions to land use for agricultural land result in higher water consumption (not significant);
- CLM scenario measures have a higher impact in water demand in agriculture than restrictions to the use of land for agriculture.

Opportunities

- Increase in diesel use (and emissions) in an integrated scenario, were possible due to reforestation, thus emissions neutrality can be achieved through cross-sectoral emissions reduction;
- Energy system measures lead to a decrease in water consumption in agriculture.

Trade-offs

- Use of irrigated practices is required to make land available for other uses (e.g. irrigated sugarcane enables low productivity cattle raising in the CLM scenario);
- The increase in electricity consumption and / or use of biomass potential discourage irrigation in agriculture.

Synergies

- Reforestation enables cross-sectoral carbon neutrality through CO_2 absorption;
- Costs of integrated practices may not be very different from sectoral, as measures across systems may average out more costly interventions.

Fig. 10. Overview of scenario insights in terms of conflicts, opportunities, trade-offs and synergies, derived from the comparison of scenario results.

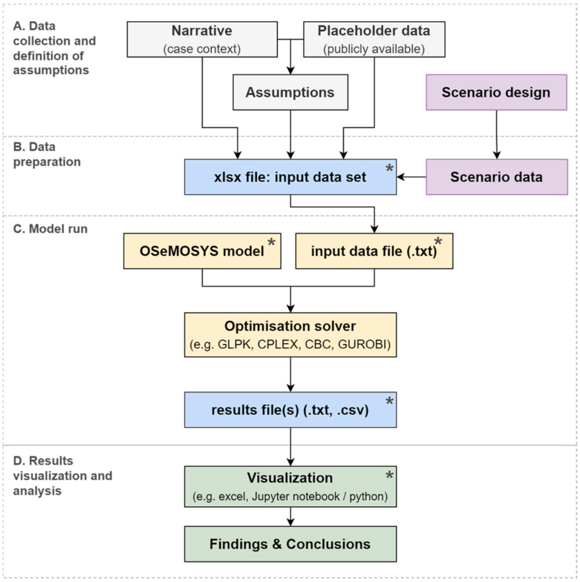


Fig. 11. Workflow diagram describing the preparation and use of the RCLEWs modelling example — the asterisk symbol (*) indicates files available in the Zenodo repository that new users can download for performing the run themselves.

of a general use case in “Open Science, and the specific use case ”Communication & Dissemination”, in which a doctoral student (primary actor) uses the OSeMOSYS-CLEWs model to develop an open-access results visualisation platform (as the main success scenario). The trigger in this use case could be the implementation of the “integrated approach” as part of a research project that involved cross-disciplinary understanding (subject area), and the student (as pre-condition) was already familiar with the Nexus approach. The platform developed could then be used for “Participatory Approaches”, and lead to various other use cases. The use case example described is identified in Table 6 using white circles. Extended descriptions of the general use cases are provided in SI (Annex I), as well as how a same specific use case can be explored in different contexts (Annex J).

The use cases described are examples of entry points of the OSeMOSYS-CLEWs exercise in various contexts. They do not intend to be comprehensive, but instances of its multiple applications. Most importantly, they illustrate the interconnectedness of Nexus research actors. They highlight the importance of institutional coordination towards incorporating the approach in policy and planning while providing elements that can guide the successful structuring of trans-disciplinary cooperation. Even though the use cases can be implemented independently, significant benefits would be harvested if performed in an integrated manner. On the one hand, open science practices have an essential and transversal role of making the tools available and ensuring methods are transparent and transferable. On the other, CoPs can assist the effort by enhancing tool development, collaboration and dissemination, while the implementation of the approach can be streamlined via multi-institutional efforts.

4. Conclusions

Quantitative analysis in Nexus assessments plays a critical role in elucidating cross-system dynamics and exploring alternative futures related to changes in natural systems or policy and management decisions. Tools that can support such analyses are needed. These should be flexible enough to adapt to representations’ requirements and available data, sustain added complexity opportunities and be relatively easy to understand and implement. For their advancement, they would benefit from community development, be part of research agendas, and be transferable to different contexts.

The modelling example explained in this paper was developed with that aim, deviating from the idea models are a “black box”. It provides future practitioners with the basic concepts of the approach, how a CLEWs representation can be performed, what type of data and assumptions it needs, and what questions can investigate. In the paper, we describe the use of OSeMOSYS as a single-model framework for CLEWs applications by providing a detailed description of model development and analysis of an illustrative national case, which was not available before. Uses of the integrated model example were then discussed in the learning, dissemination, adoption and advancement of the Nexus approach and its application in academia, capacity development activities, participatory processes, and open science. The simple model can be used as a Nexus knowledge transfer tool and to teach Nexus modelling concepts in general, using non-proprietary tools, be adapted to different contexts and used as an interface to other tools. It can also support the science-policy interface by facilitating, among stakeholders, the understanding of how quantitative analyses are performed, how data is used,

Table 6

Examples of use cases for the OSeMOSYS-CLEWs exercise and similar approaches, with primarily applications identified with coloured boxes. Notwithstanding, the authors recognise that combinations not marked could also exist and are not identified in the table as perceived less dominant. White dots displayed in the "Open Science" column refer to a use case example described in the text to elucidate the table's use.

		General Use Case			
		Academia	Capacity Development	Participatory Approach	Open Science
Specific Use Case	Learning (Education) & Research	🟧			🟪
	Co-development	🟧	🟦	🟩	🟪
	Modelling capacity		🟦		
	Data Access & Sharing		🟦	🟩	
	Scenario Development		🟦	🟩	
	Analysis Validation & Consultation		🟦	🟩	🟪
	Science-based evidence		🟦	🟩	🟪
	Communication & Dissemination			🟩	🟪 ●
Actors (stakeholders & primary)	1st & 2nd Cycle	🟧			🟪
	3rd Cycle	🟧	🟦	🟩	🟪 ●
	Academic Staff	🟧	🟦	🟩	🟪
	Gov. Technical Officials		🟦	🟩	
	International Organisations		🟦	🟩	
	High-level Officials		🟦	🟩	
	Other Stakeholders (e.g. research institutes, consultants)		🟦	🟩	🟪
Subject-Area	Cross-disciplinary	🟧	🟦	🟩	🟪 ●
	System / Sector specific	🟧	🟦	🟩	🟪
	Other (e.g. Industry, Business, Social)				🟪
Trigger	Interdisciplinarity	🟧	🟦		🟪
	Integrated Approach	🟧	🟦	🟩	🟪 ●
	Advancement of Science	🟧			🟪
	Resources Management		🟦	🟩	
	Sustainable Development (including international agendas)	🟧	🟦	🟩	🟪
Pre-conditions	Sectoral Knowledge	🟧	🟦	🟩	🟪
	Nexus knowledge	🟧	🟦	🟩	🟪 ●

(*continued on next page*)

Table 6 (*continued*)

		General Use Case			
		Academia	**Capacity Development**	**Participatory Approach**	**Open Science**
	Modelling or participation in Capacity Development initiatives	🟧	🟦	🟩	
	Other experience		🟦	🟩	🟪
Main success scenario	Building core competencies on systems thinking and integrated planning	🟧	🟦	🟩	
	Identification of trade-offs, opportunities and integrated solutions		🟦	🟩	
	Role of science-based evidence for decision making	🟧	🟦	🟩	
	Methods and tools development (e.g. nexus, CLEWs, OSeMOSYS, etc.)	🟧			🟪 •
	Other	🟧			🟪

and what limitations may exist. Inter- and transdisciplinary practices can be fostered via the modelling example and by developing a context-specific model, providing a common ground to actors involved in a study. Lastly, its openness can contribute to the advancement of Nexus research by promoting its application and developing a wider community of users and practitioners.

Academics, researchers, government officials, institutional actors, and all associated with the CLEWs approach, and the Nexus in general, will find this paper instrumental for the communication of the approach in starting Nexus discussions and dialogues. The use cases can assist with the design of CLEWs-type analyses. Most importantly, they provide a broader perspective for the coordinated planning of activities around a Nexus assessment or the development of research plans. The paper will help anyone seeking to enhance their understanding of the CLEWs nexus and, in particular, of one of the quantitative approaches used in its analysis.

CRediT authorship contribution statement

Eunice Ramos: Conceptualization, Methodology, Investigation, Software, Data curation, Visualization, Writing- Original draft preparation. **Vignesh Sridharan:** Conceptualization, Methodology, Investigation, Visualization, Writing- Reviewing and Editing. **Thomas Alfstad:** Conceptualization, Methodology, Writing- Reviewing and Editing. **Taco Niet:** Writing- Reviewing. **Abhishek Shivakumar:** Writing- Reviewing. **Mark Howells:** Writing- Reviewing. **Holger Rogner:** Writing-Reviewing. **Francesco Gardumi:** Conceptualization, Supervision, Writing- Reviewing and Editing.

Declaration of Competing Interest

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

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.envsci.2022.07.007.

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