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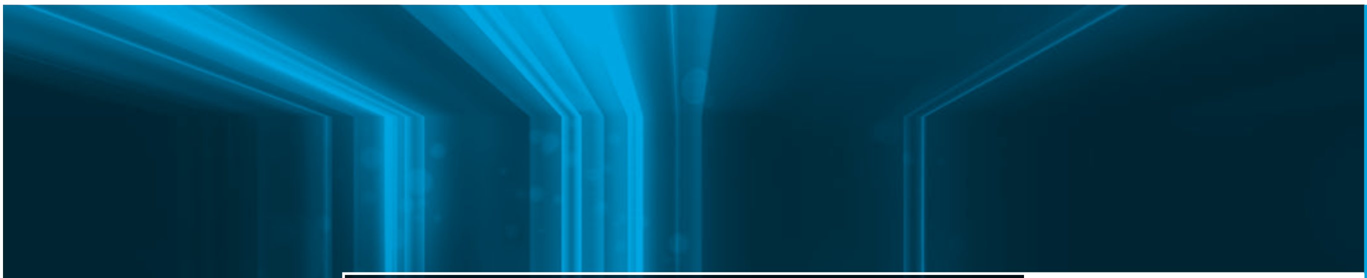

IAEA TECDOC SERIES

No. 2065

The Climate, Land, Energy and Water Framework

A Methodology Handbook

THE CLIMATE, LAND, ENERGY AND WATER FRAMEWORK

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The Agency’s Statute was approved on 23 October 1956 by the Conference on the Statute of the IAEA held at United Nations Headquarters, New York; it entered into force on 29 July 1957. The Headquarters of the Agency are situated in Vienna. Its principal objective is “to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world”.

IAEA-TECDOC-2065

THE CLIMATE, LAND, ENERGY AND WATER FRAMEWORK

A METHODOLOGY HANDBOOK

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 2024

For further information on this publication, please contact:

Planning and Economic Studies Section
International Atomic Energy Agency
Vienna International Centre
PO Box 100
1400 Vienna, Austria
Email: Official.Mail@iaea.org

Printed by the IAEA in Austria
August 2024
https://doi.org/10.61092/iaea.uiu5-lz0j

IAEA Library Cataloguing in Publication Data

Names: International Atomic Energy Agency.
Title: The climate, land, energy and water framework / International Atomic Energy Agency.
Description: Vienna : International Atomic Energy Agency, 2024. | Series: IAEA TECDOC series, ISSN 1011-4289 ; no. 2065 | Includes bibliographical references.
Identifiers: IAEAL 24-01702 | ISBN 978-92-0-127224-9 (paperback : alk. paper) | ISBN 978-92-0-127324-6 (pdf)
Subjects: LCSH: Sustainable development. | Climatic changes. | Climate change mitigation. | Power resources — Environmental aspects.

FOREWORD

Ensuring universal access to energy, food and water, while addressing challenges such as climate change, is critical to sustainable development. These objectives are highly interdependent and responding to one dimension (e.g. improving energy access) can have positive or negative impacts on others (e.g. climate change mitigation). To support Member States in elaborating integrated strategies, including to achieve the Sustainable Development Goals (SDGs), from 2009–2010, the IAEA developed the climate, land, energy and water (known as CLEW) framework in cooperation with other United Nations organizations and scientific experts.

The CLEW framework expands established IAEA activities strengthening Member States' capacities to elaborate sustainable energy strategies by linking different resource assessment approaches and methodologies to address SDG 2 on zero hunger; SDG 6 on clean water and sanitation; SDG 7 on affordable and clean energy; SDG 13 on climate action; and SDG 15 on life on land. This complements other major IAEA activities in capacity building in nuclear energy technology development, the sustainable management of agriculture and water resources and the monitoring of and adaptation to climate change.

This publication is intended to serve as a reference for practitioners in Member States, international organizations, non-governmental organizations and elsewhere seeking to apply integrated assessment approaches and methodologies to develop coherent sustainable and climate resilient energy, water and land use strategies.

The IAEA officer responsible for this publication was H. Turton of the Division of Planning, Information and Knowledge Management.

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CONTENTS

1. INTRODUCTION 1
    - 1.1. BACKGROUND 1
    - 1.2. OBJECTIVE 2
    - 1.3. SCOPE 2
    - 1.4. STRUCTURE 3

2. ELABORATING THE CLEW NEXUS 4
    - 2.1. THE LAND–WATER NEXUS 5
    - 2.2. THE ENERGY–WATER NEXUS 6
    - 2.3. THE LAND–ENERGY NEXUS 8
    - 2.4. CLIMATE CHANGE: THE OVERARCHING ISSUE 10

3. THE INTEGRATED CLEW FRAMEWORK 13
    - 3.1. MODELING THE ENERGY, WATER AND LAND SYSTEMS 13
    - 3.2. THE CONCEPT OF CLEW 14
    - 3.3. ADVANTAGES AND SHORTFALLS OF THE MODULAR APPROACH 15
    - 3.4. OTHER CHALLENGES AND LIMITATIONS OF THE CLEW APPROACH 16
    - 3.5. AREAS OF APPLICATION OF THE CLEW FRAMEWORK 16

4. IMPLEMENTATION OF THE CLEW FRAMEWORK 18
    - 4.1. SETTING UP A CLEW STUDY 18
        - 4.1.1. Systems profiling 18
        - 4.1.2. Pre-nexus assessment 20
        - 4.1.3. Model development 20
        - 4.1.4. Analysis of the results 21
        - 4.1.5. Reporting 21
    - 4.2. MODELING THE CLEW SYSTEMS 21

5. THE CLEW REFERENCE SYSTEM 24

6. CONCLUDING REMARKS ON THE CLEW FRAMEWORK 28

REFERENCES 31

CONTRIBUTORS TO DRAFTING AND REVIEW 35

1. INTRODUCTION

1.1. BACKGROUND

The world is confronted with multifaceted and interconnected social, economic and environmental challenges. Achieving the goals of sustainable development requires approaches that recognize that the systems that underpin human societies and the natural environment are interlinked and depend on and interact with each other in a highly complex manner.

The sustainable management of natural resources, such as energy, land and water, is central to satisfying human needs while addressing challenges such as climate change in a way that ensures that future generations are also able to meet their own needs. Traditionally, energy, water and land have been managed without fully considering the relationships between these three resources. Little consideration has been given, for instance, to the impact on food security and water resources of growing crops for biofuel production. However, energy security, water security and food security are closely intertwined: for instance, food, feed and fibre production consume water and energy; water production requires energy and is impacted by land use; and energy production relies on water and land resources. The interactions among the three sectors are becoming increasingly complex and dynamic as economic development, population growth and urbanization combine to exert additional pressure on resources.

Climate change is also expected to continue exacerbating energy, water and land challenges. Additionally, policies adopted in response to climate change may impact or be impacted by the management of water, energy and land resources. Similarly, policies and practices in the land, water and energy sectors — including the adoption of climate-smart agriculture or digital solutions in the energy sector — have the potential to capitalize on synergies with climate change mitigation and adaptation goals.

Figure 1 conceptually depicts the interactions between the water, land and energy sectors within the envelope of climate change. For instance, the promotion of a renewable energy technology that consumes water might lead to a reduction in carbon dioxide emissions while increasing water consumption. At the same time, climate change may affect the availability of resources and increase the uncertainty faced by decision makers. For instance, the impact of climate change on available water might limit renewable energy aspects of the climate strategy a country can pursue; or necessitate additional water extraction or desalination, requiring additional energy and offsetting the benefits of the switch to renewable energy.

In September 2015, the United Nations General Assembly adopted the 2030 Agenda for Sustainable Development, including 17 sustainable development goals (SDGs). Crucially, Agenda 2030 reflects an improved understanding of the complexity of the relationships between the different aspects of development, incorporating an integrated, systematic approach that balances the three dimensions of sustainable development: economic, social and environmental. The SDGs cover a wide spectrum of topics, from food security, poverty and gender inequality to inclusive economic development, climate change and health, among others. Progress toward 12 of the SDGs is directly related to the sustainable use of resources such as land, food, water, energy and materials. Shortly after the adoption of Agenda 2030 in 2015, the international community negotiated the Paris Agreement on climate change, with the goal to hold global warming to well below 2°C, and pursue efforts to limit the increase to 1.5°C, compared to pre-industrial levels.

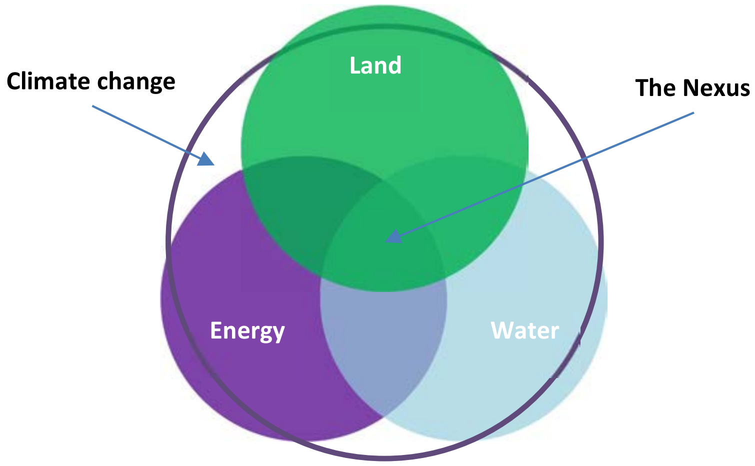

FIG. 1. The climate, land, energy and water (CLEW) nexus.

In addressing the daunting challenge of climate change while fulfilling simultaneous demands for food, water and energy in a sustainable manner, 'silo thinking' is increasing unsuitable. Energy, water and land need to be looked at as a 'system' influenced by climate change by adopting a holistic approach that explicitly defines the links between the single components of the Climate, Land, Energy and Water (CLEW) nexus. Such an approach can help to avoid unintended consequences that might arise when an intervention addressing one resource impacts another part of the nexus. More broadly, it can provide a framework to inform planning, policy and decision making by identifying potential synergies and trade-offs in the production and use of energy, water and land in the context of finite and often stressed natural resource assets, and the challenges of climate change. This approach, by adopting a more structured planning method which captures the interdependency of resource use and availability, aims to achieve a more optimal allocation of resources and improved economic efficiency and development, while reducing negative environmental and health impacts.

1.2. OBJECTIVE

The objective of this publication is to provide guidance — or a handbook — on the application of the CLEW nexus framework approach developed by IAEA with other UN agencies and scientific partners, which integrates quantitative tools for climate, land, energy and water modelling [1, 2].

1.3. SCOPE

This publication introduces and illustrates the interlinkages between energy, water and land systems and how all three impact and are impacted by climate change, demonstrating why these systems need to be assessed in an integrated way. Furthermore, this handbook shows practitioners how to apply the CLEW nexus framework approach.

1.4. STRUCTURE

The publication is structured in four main sections.

Section 2 first elaborates the CLEW nexus, introducing and describing in detail each resource axis of the nexus (i.e., land–water, energy–water, land–energy) as well as the overarching connections with climate change.

Section 3 presents the integrated CLEW assessment framework developed by IAEA together with other UN organizations and scientific experts. The section covers the CLEW concept, approaches to modelling CLEW systems, including advantages and disadvantages of different approaches, and applications of the CLEW approach along with limitations.

Section 4 provides a step-by-step guide on implementing the CLEW framework. This includes the steps in setting up a CLEW study, starting from initial profiling of the resource systems of interest and pre-nexus assessment, through model development, to analysis and reporting. Modelling of CLEW systems is also discussed in this section.

Section 5 introduces and explains the utility of a conceptual 'reference system' to illustrate and visualize the production chains in a CLEW modelling analysis. The reference system represents highly complex and interlinked resource system interactions in the form of a simplified, manageable and organized model structure, which is valuable both for practitioners and for communicating the CLEW approach and results.

2. ELABORATING THE CLEW NEXUS

Global hunger creates a cycle of poverty and exacerbates many development challenges. It causes individuals to be less productive and more prone to disease, which in turn makes them less able to improve their livelihoods or earn a better income. Yet, despite the Green Revolution and significant advances in agriculture, 2.37 billion people (30 percent of the global population) still face moderate or severe food insecurity [3].

Demand for water has been growing twice as fast as the global population over the last few decades. Global freshwater withdrawals from surface water and groundwater sources have increased by roughly 1 percent per year since the 1980s, even accounting for an apparent slowing (to 0.6 percent per year) over the past 15 years. As a result, 2.3 billion people (30 percent) today live in water stressed countries and 730 million people (9 percent) live in high and critically water stressed countries [4].

World energy consumption continues to rise, as developing nations industrialize, and as consumers in developed nations buy more energy consuming appliances. Despite this relentless growth in energy consumption, many people, primarily in developing and emerging economies, suffer from energy poverty. Currently, 32 percent of the world population (~2.5 billion people) lack access to clean cooking energy solutions and 10 percent lack access to electricity [5].

Human activities are releasing greenhouse gases (GHGs) into the atmosphere. Rising concentrations of carbon dioxide, methane and other long lived gases are already changing the climate. Compared with the end of the pre-industrial era (1850–1900), global temperatures have increased by an average of more than 1.1°C, with 2015 to 2021 being the warmest seven years on record [6].

The global population has been growing by approximately 80 million people annually over the past decade. Moving forward, the United Nations' medium variant projection expects the global population to reach 8.5 billion in 2030, 9.7 billion in 2050 and 10.4 billion in 2100 [7]. Population growth remains especially high in the group of 46 least developed countries. Additionally, most of this growth is expected in urban areas, which surpassed the population of rural areas for the first time in history in 2007. By 2050 around two thirds of the global population are predicted to be living in urban settlements [8].

Over time, stress on the energy, water and land use sectors will increase in line with these demographic trends as well as economic and consumption developments. Long term estimates indicate that by 2050 global energy use could increase by nearly 50 percent compared with 2020 [9]. At the same time, annual global water demand for all uses, estimated to be about 4600 km^3 in 2010, could increase to 5500–6000 km^3 by 2050 [10, 11]. Furthermore, compared to 2005/2007 levels, 60 percent more food will be needed by 2050 to feed a growing global population, and irrigated food production will need to increase by more than 50 percent over the same period [12]. Additionally, if a transformation to green fuels materializes, more feedstocks will be required for the bioenergy market.

Implementation of the Paris Agreement on climate change requires rapid economic and social transformation, based on the best available science, to hold the increase in global temperature to well below 2°C. However, by late 2023, national commitments still imply an increase of about 8.8 percent in global GHG emissions in 2030 compared with 2010. According to the latest findings of the Intergovernmental Panel on Climate Change, such an increase, unless actions are taken immediately, may lead to a temperature rise of about 2.5°C by the end of the century [13].

As demonstrated by the adoption of Agenda 2030, the global community recognizes that: (a) equitable access to and effective use of land resources is essential to address the prevalence of hunger; (b) careful management of water resources is essential for ensuring availability of safe water and sanitation for all; and (c) access to energy is essential to support basic comforts and productive capabilities, among other goals. This is reflected explicitly in three SDGs:

- SDG 2 — End hunger, achieve food security and improved nutrition and promote sustainable agriculture;
- SDG 6 — Ensure availability and sustainable management of water and sanitation for all;
- SDG 7 — Ensure access to affordable, reliable and modern energy for all.

These goals need to be achieved in parallel with protecting the environment, including responding to climate change, reflected in:

- SDG 13 — Take urgent action to combat climate change and its impacts.

Long term sustainability requires acknowledging that many of the resources that support development (such as water, land and energy) are finite, and that their uses are interlinked. It is also dependent on maintaining and supporting vital ecosystems. Development can only be sustainable if it works within those constraints, over time, and across sectors and locations. The interlinkages between land, water and energy are elaborated in the following subsections.

2.1. THE LAND–WATER NEXUS

Agriculture is by far the largest consumer of freshwater resources, reflecting the critical role of water in food security (i.e., the state in which people have access to sufficient, safe, nutritious food to maintain a healthy and active life). Globally, more than 70 percent of withdrawals from waterbodies and groundwater are for agricultural usage [14], with approximately 40 percent of the world's food produced on irrigated land [15]. Huge investments in additional irrigation systems, especially in the densely populated regions of South and Southeast Asia, between the 1960s and 1980s were essential to achieving the gains from high yielding, fertilizer responsive crop varieties. The availability of small, cheap diesel or electric pumps has revolutionized how farmers invest in self managed groundwater irrigation.

At the same time, these developments have also resulted in a massive overuse of water and falling groundwater tables. For example, in India around 28 percent of groundwater blocks were estimated to be in a semi critical, critical or overexploited condition by 2004 [16], mainly attributable to the rising demand for groundwater from agriculture. Nine states reliant on electrical groundwater pumping accounted for 85 percent of India's stressed groundwater.

The overexploitation of groundwater makes it necessary to pump at greater depths, and consequently increases the cost of pumping and associated energy use. Moreover, overexploitation of groundwater can lead to contamination and may give rise to increased salinity, particularly in coastal areas. Of the water withdrawn for irrigation, consumption "can range from 30–40% for flood irrigation to 90% for drip irrigation…[while the]…rest recharges groundwater or contribut[es] to drainage or return flows” [17] potentially leading to higher salt concentrations and contamination with nutrients, pesticides and herbicides. With the increased use of fertilizers and agrochemicals in modern agriculture, this may result in the accumulation of salt and contaminants at levels that could ultimately result in infertile soil, threatening food security. Globally, 45 million hectares, or approximately 20 percent of the world’s irrigated lands, are salt affected due to anthropogenic reasons (human induced salinization) and thus are essentially commercially unproductive [18].

2.2. THE ENERGY–WATER NEXUS

Water is a key input to energy production as illustrated in Table 1 [19]. Global water use for primary energy production and power generation is estimated at approximately 400 billion cubic metres per year, or roughly 10 percent of total worldwide water withdrawals [20]. However, this excludes substantial and uncertain water usage in the production of traditional biomass (primarily wood fuel derived from trees and shrubs), which accounts for a relatively high share of the energy mix in some world regions (e.g. approximately 22 percent in Africa, compared to a world average of 8 percent). When this is included in the consideration of primary energy, annual water requirements for global primary energy production are estimated to increase by around 1500 billion cubic metres [21].

TABLE 1. WATER USES IN ENERGY PRODUCTION. Source: reproduced with minor modifications from Ref. [19] with permission courtesy of the OPEC Fund for International Development.

Sector	Fuel	Description of water use
Primary energy	Oil and gas	Drilling, well completion and hydraulic fracturing; secondary and enhanced oil recovery; oil sands mining and in situ recovery; upgrading and refining.
	Coal	Cutting and dust suppression in mining and hauling; washing to improve quality; revegetation of surface mines; long distance transport via coal slurry.
	Biofuels	Irrigation for feedstock crop growth, wet milling, washing and cooling in conversion processes.
Power generation	Thermal	Boiler feed; cooling for steam condensing; pollutant scrubbing for emission control.
	Solar thermal and geothermal	Boiler feed; cooling for steam condensing; cleaning of reflective surfaces.
	Hydropower	Electricity generation; reservoir storage.
	Photovoltaics	Panel cleaning.

In addition, energy is needed throughout the water supply chain and in wastewater treatment, as summarized in Table 2 [19]. The International Energy Agency estimated that, in 2014, the worldwide water sector consumed 120 million tons of oil equivalent, equivalent to approximately 1.3 percent of the global final energy consumption for that year [20, 22]:

> “About 60 percent of that energy is consumed in the form of electricity, corresponding to a global demand of around 820 terawatt-hours (TWh) (or 4 percent of total electricity consumption)…. The rest is thermal energy, half of which is used in diesel pumps, mainly to pump groundwater for agricultural purposes. The remainder is used for desalination, mainly in the form of natural gas.” [23]

Although the amount of energy consumed by the water sector may appear relatively modest on a global level, in some parts of the developing world, the cost of energy to supply water can easily consume a large proportion of a municipality's total budget.

In addition to energy used in the supply of water, a substantial amount of energy is also needed to produce hot water and steam for various residential, commercial and industrial applications. In 2019, the residential sector accounted for 13 percent of the world final energy consumption [24]. In this sector, up to one third of the consumed energy is for water heating in industrialized countries, as seen in Fig. 2. When added to energy for cooking, this percentage could be as high as 90 percent in developing countries, especially in rural areas.

TABLE 2. ENERGY USES IN WATER SUPPLY AND WASTEWATER MANAGEMENT. Source: reproduced with minor modifications from Ref. [19] with permission courtesy of the OPEC Fund for International Development.

Sector	**Process**	**Description of energy use**
Water supply	Extraction	Deep well pumping; surface source pumping.
	Sea and brackish water desalination	Feed pumping; high pressure reverse osmosis pumping; heat for thermal processes.
	Treatment	Dosing pumps for chemical treatment; pumps, fans, agitators, blowers for physical treatment.
	Conveyance	Submersible, shaft turbine, horizontal or vertical centrifugal pumping systems to distribution networks; booster pumping.
	Distribution to end consumers	Horizontal or vertical centrifugal pumping.
Wastewater	Sewage and rainwater piping	Horizontal or vertical centrifugal pumping.
	Wastewater treatment	Pumps, fans, agitators, blowers.
	Distribution to end consumers	Horizontal or vertical centrifugal pumping.

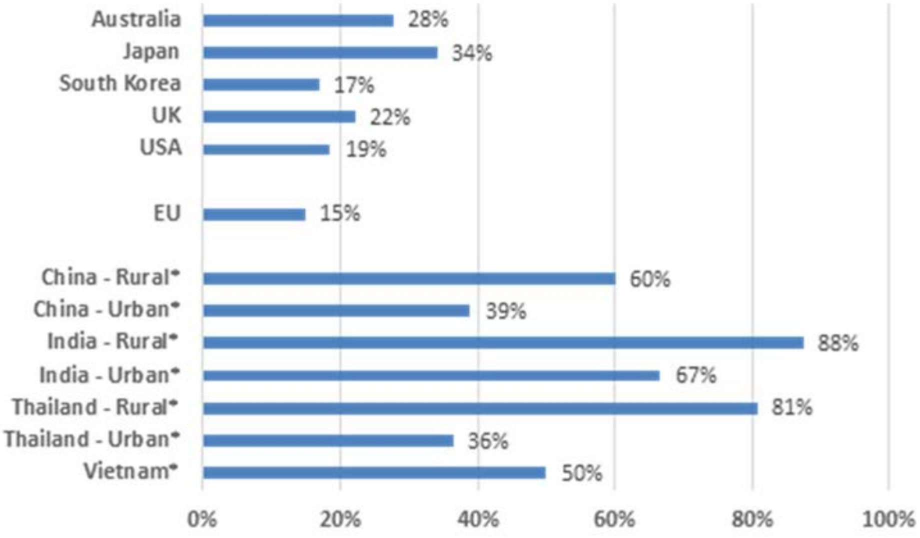

FIG. 2. Share of energy for water heating in residential energy consumption in selected countries. Note: asterisk (*) indicates that the estimate includes energy used for cooking. Source: adapted from Refs [25–27].

The interlinkages between water and energy highlight several risks that need to be understood and properly managed. These include, among others:

- Water shortages can result in reduced energy production.
- Restricted access to affordable energy can hamper the delivery of water and provision of sanitation.
- Increases in the temperature of water supplied to thermal power plants for cooling can reduce the efficiency of the power plant (and power plants may also face restrictions on discharging warmer cooling water).
- Interruptions to normal river flow caused by large hydropower dams may result in saltwater intrusion into deltas.
- Large hydropower reservoirs can act as heat sinks, resulting in higher water temperatures and affecting upstream and downstream ecosystems. This warm water can also impact the efficiency of thermal power plants.

2.3. THE LAND–ENERGY NEXUS

While the technological and industrial developments underpinning the agricultural green revolution led to an enormous improvement in crop yields, they also dramatically increased the energy consumption in farming and food production. In 2019, world energy use in agriculture for food crop and non-food crop production amounted to approximately 10 exajoules, about 2.4 percent of the total final energy consumption [28, 24]. This excludes energy use for manufacturing of fertilizers, agrochemicals, and machinery.

However, as seen in Fig. 3 [19], energy is needed in all steps along the agrifood chain — from food crop production to food cooking — both directly (for production, processing, and transport) and indirectly (for manufacturing of fertilizers, agrochemicals, and machinery). Today, the entire agrifood sector is responsible for around one third of the world's total final energy demand [29]. At the global level, about 22 percent of the total is consumed before reaching the farm gate (including fisheries), 43 percent in food processing and distribution, and 35 percent in retail, preparation and cooking. The dependence of food production on energy inputs makes it particularly sensitive to energy prices. In low GDP countries, a smaller share of energy is used on the farm and a greater share for cooking.

For the last quarter century or so, supply security, climate change and local development have been the drivers for the expanded use of renewable energy sources. In particular, the world's production of transportation biofuels grew more than ten-fold between 2000 and 2020, as shown in Fig. 4 [30]. In 2018, the share of biofuels in the global transportation sector was around 3.1 percent [31].

FIG. 3. Energy uses in the food sector.

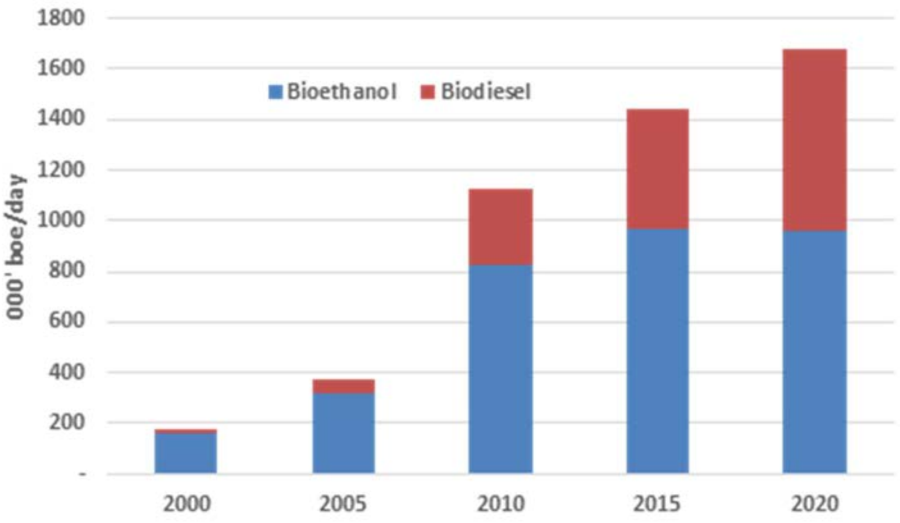

FIG. 4. Global biofuels production. Source: [30].

Today, the bulk of biofuels — principally bioethanol and biodiesel — are still produced from crops that can also be used for food, despite ambitious targets and considerable research aimed at development of advanced or 'second generation' biofuels, mostly those derived from cellulosic biomass. As a result, biofuel production is a major driver of agricultural commodity demand and prices. For instance, the International Monetary Fund projected that higher ethanol production in the USA accounted for 60 percent of the global increase in corn consumption in 2007 [34]. They also estimated that biofuel production in the USA and European Union accounted for the bulk of demand growth for soybean and rapeseed oil from 2005 to 2007.

In addition, increasing biofuels production, whether based on food crops or dedicated 'energy crops', has the potential to increase competition for water resources and exacerbate water stress. Per unit of energy content, biofuels require hundreds of times the amount of water that is needed to produce fossil based transportation fuels [32, 33, 21].

Beyond biofuels, other forms of energy production, transmission, distribution and storage also require the use of land. In addition to the land occupied by energy infrastructure itself, energy resource extraction can be a significant land user. Surface coal mining and land flooding for hydropower reservoirs are prime examples. Waste disposal can also account for significant land use for nuclear power plants, as well as for low-energy-value coal mining and the disposal of coal combustion waste remaining after coal has been burned. Solar and wind energy convertors require land for mining the materials used in their manufacture (e.g. silicon and neodymium), but the land needed for this purpose is insignificant in comparison to hydropower and coal mining. The major drawback for solar and wind, however, is the large amount of land occupied by the power plants. In a wind farm, most of the land area is due to necessary spacing between turbines, which is typically between 5 to 10 rotor diameter lengths [35]. Similarly, with an energy density of 1 kilowatt per square metre or less anywhere on Earth, and the need to avoid shading of incident solar radiation, large land requirements are a major consideration for solar power plants using either photovoltaic or concentrated solar power technologies.

The energy land footprint varies from one energy source to another. Furthermore, there is variation between energy systems that use the same resource, due to local circumstances (e.g.

depth of coal seams, spacing of gas and oil wells, biomass yields, dam height, solar insolation level, wind regime and land topography). Table 3 shows the typical land requirement for a range of energy systems or electricity generation and transport fuels [36].

TABLE 3. LAND USE INTENSITY PER MEGAWATT HOUR PRODUCED

Product	**Primary Energy Source**		**m^2/MW·h**
Electricity	Coal	Underground	0.2
		Surface	5.0
	Natural Gas		0.2
	Nuclear		0.1
	Renewables	Biomass (from crops)	500
		Geothermal	2.5
		Hydropower (large dams)	10
		Solar – concentrated solar power	15
		Solar – photovoltaic	10
		Wind	1
Liquid Fuels	Fossil oil		0.4
	Biofuels	Corn	230
		Cellulose, residue	0.1
		Cellulose, short rotation coppice	500
		Soybean	400
		Sugarcane (from juice)	230
		Sugarcane (residue)	250

Note: m^2/MW·h — square metres per megawatt-hour.

In total, it is estimated that the current land used for energy systems is relatively negligible, at approximately 2 percent of global land (149 million hectares) [36]. Out of this, approximately 48 percent, or 72 million hectares, is used for electricity production [37]. Depending upon the electricity portfolios of future energy scenarios, studies conclude that there is potential for a significant increase in land use for electricity production in the coming decades, ranging from an additional 30–80 million hectares for physical footprint to an additional 80–800 million hectares when spacing is included [37]. This could significantly reduce the amount of land available for other purposes, such as agriculture, commercial forestry or environmental protection.

2.4. CLIMATE CHANGE: THE OVERARCHING ISSUE

As shown in Fig. 5, energy, agriculture and land use change together account for nearly 90 percent of global GHG emissions [38]. Clearly, any efforts towards climate change mitigation need to focus closely on these sectors. At the same time, the energy, land and water systems are vulnerable to climate change. This is elaborated in the following paragraphs, which summarize some of the effects outlined the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [39].

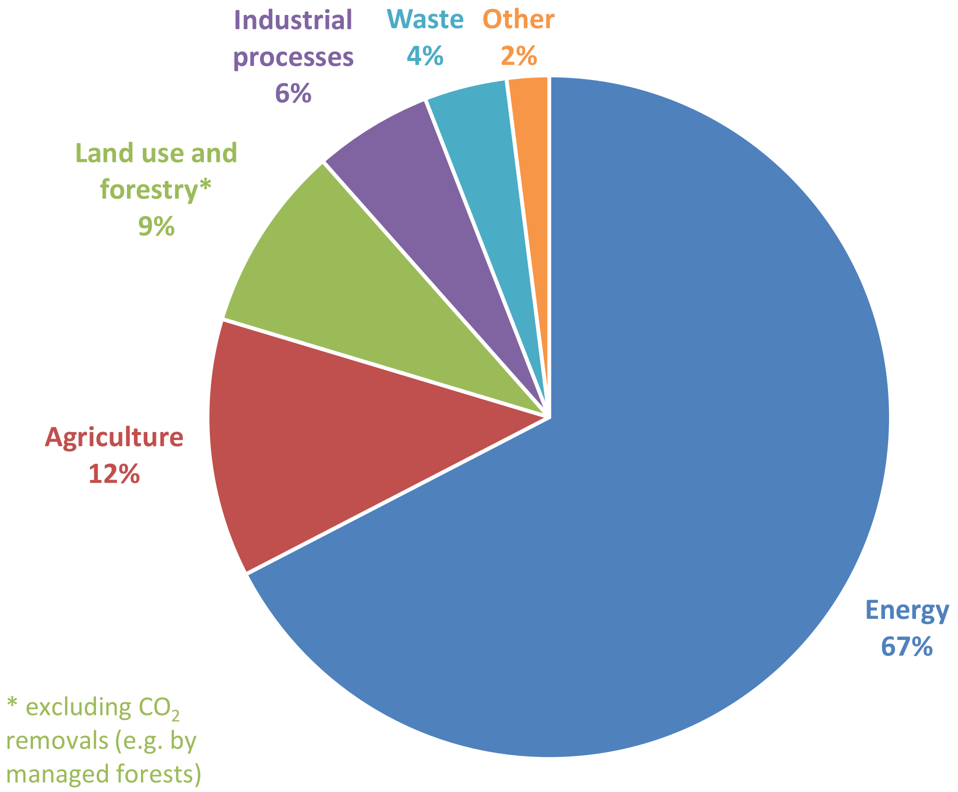

FIG. 5. Contributions to GHG emissions by sector, 2020. Source: [38].

Climate change impacts the world's water resources in complex ways, affecting almost the entire water cycle and placing drinking water supplies, food production and other activities under increasing pressure around the world [40].

Higher temperatures will mean increased evaporation and transpiration from oceans, lakes, soil and plants. In some locations, the reduction in surface water and drier soils and vegetation will result in increasingly frequent and severe droughts. Conversely, many locations are expected to experience large increases in the intensity and frequency of heavy precipitation events, including thunderstorms, caused by warmer, wetter air. Higher ocean surface temperatures and changing circulation patterns are also influencing where precipitation falls, impacting both agriculture and natural ecosystems. Increasingly extreme precipitation events are expected to lead to more intense flooding, which can endanger human lives, kill livestock, damage crops and strip nutrients from the soil. Climate change induced droughts have similar devastating impacts on agriculture.

Naturally, reductions in surface and ground water due to climate change can lead to reduced water availability and to water supply shortages, particularly in drought prone areas. In addition, droughts can lead to a deterioration of water quality and cause intrusion of saline water into groundwater as well as increased pollution concentrations in waterbodies receiving wastewater. At the same time, increased surface runoff from heavier rainstorms has the potential to flush additional pollutants into waterbodies, making it more energy intensive and expensive to provide clean drinking water and harming fish and other wildlife. Climate change also means that temperate regions are likely to receive more of their precipitation as rain rather than snow as air temperatures increase. This means less water stored in the snowpack to replenish water supplies during the spring and summer, leading to drier conditions. Higher rainfall (and lower snowfall) can also accelerate the melting of snow that is already on the ground. In addition to disrupting the water cycle, climate change will affect demand for water. Higher temperatures and evaporation will change how and how much water is used in many areas.

Beyond these impacts from global climate change caused by emissions of GHGs, other activities, particularly changes to land use, can also influence local and regional climate. Land use changes can affect the amount of solar radiation absorbed and converted to heat — referred to as 'albedo' and exemplified by the urban heat-island effect — which can influence climate on local, regional, and possibly global, scales. Moreover, the impact on albedo from decreased plant cover and dry bare soil can also affect convection, cloud formation and precipitation. The reduced rainfall in turn can have an adverse effect on plants and exacerbate the original loss of plant cover.

Higher temperatures, changing precipitation patterns and increasingly frequent extreme events are already impacting food security. The yields of key crops (e.g., maize and wheat) have declined in many lower latitude regions — for example, in parts of the Mediterranean — and increased in many higher latitude regions over recent decades [41]. Fruit and vegetable production, a key component of healthy diets, is also vulnerable to climate change. Climate change is also affecting the distribution of agricultural pests and diseases in many regions. Together, these changes are increasing the risk of major disruptions to food production systems. Global crop and economic models project an increase of up to 29 percent in cereal prices in 2050 due to climate change, which would impact consumers globally [41]. Low income consumers are particularly at risk, with models projecting up to 183 million additional people at risk of hunger due to climate change [41].

Furthermore, climate change impacts energy use and production. While warmer weather can reduce heating fuel requirements, hot and humid air may increase the demand for electricity for air conditioning and refrigeration. At the same time, changes to precipitation patterns and water shortages due to droughts can result in changes to electricity production from hydropower plants. Additionally, reduced availability of cooling water, and higher water temperatures, may impact thermal power plant operations, causing a drop in the efficiency and electricity output. Also, power generation that relies on dry cooling may face additional challenges owing to the sensitivity of dry-cooled power plants to meteorological conditions. In particular, high ambient temperatures can reduce generating capacity by up to 15 percent [42].

Higher temperatures can also affect electricity transmission and the performance of solar photovoltaic generators. Additionally, if climate change alters the large scale air flow or local conditions such as surface roughness, thereby affecting the pattern of near surface winds upon which wind energy potential is strongly dependent, it can also alter the available wind resources. This is especially important in the planning of wind farms. Moreover, the increasing frequency and severity of extreme weather events also has the potential to cause major disruptions to energy infrastructure more broadly and necessitate significant measures to adapt energy systems.

3. THE INTEGRATED CLEW FRAMEWORK

The previous sections outlined the importance of land, water, energy, food security and climate stability to sustainable development. They also illustrated the highly complex and dynamic interactions between the land, energy and water domains as well as linkages with both climate change adaptation and mitigation. All of this underlines the need for an integrated approach to policy and strategy formulation.

While integrated environmental assessments are regularly applied at the project level in many countries, assessments at the national level for energy, water and land use are traditionally conducted in isolation by separate government agencies. However, in addressing the daunting challenge of fulfilling the simultaneous demands for food and fibre, water and energy in a sustainable manner, the conventional 'silo thinking' approach to the management of a single resource that treats other resource inputs and demand as external to the resource system is increasingly unsuitable. Interventions undertaken towards achieving one goal may very well have implications on progress towards other goals. Unintended consequences could be positive, or synergetic (i.e., a decision in one area could be conducive to another), and they could be negative, meaning progress in one could be detrimental to another, raising the issue of trade-offs between the different areas. These linkages and potential challenges exist not only horizontally across different domains, but also vertically across the different levels of governance, from the local, to the national, to the global.

With a holistic, or integrated, approach that explicitly defines the links between the single components of the CLEW nexus and can represent the effect each one has on the others, potential trade-offs and synergies can be identified and assessed, and options to mitigate negative effects or exploit positive spillovers can be analysed. This can then support policy coherence — meaning that decisions made on interventions are aligned — both horizontally across the different relevant sectors and vertically from local, to national, to global.

Moreover, an integrated approach to the CLEW nexus can provide a framework to facilitate interaction among relevant stakeholders, domain experts and decision makers during the full cycle of design, implementation, monitoring and evaluation of policies and strategies.

With these goals in mind, international organizations (including the IAEA) and scientific experts have partnered to develop the CLEW framework and methodology to provide a structured planning method that systematically captures the linkages and interdependencies between land, energy and water and formally incorporates them in policy making and planning [1]. This is intended ultimately to support decision makers to realize a more optimal allocation of resources, improved economic efficiency, lower negative environmental and health impacts, and better economic development conditions.

3.1. MODELING THE ENERGY, WATER AND LAND SYSTEMS

Given the high level of complexity, understanding interlinkages between the systems of land, energy, water and climate, and related policy interactions, is clearly a challenge. Mathematical modelling and quantitative analysis tools constitute one of the means to address these complexities and the associated uncertainties. Of course, such tools have long been applied to support policy in a wide range of sectors and circumstances. For example, the MESSAGE[1] [43], OSeMOSYS[2] [44], MARKAL[3] [45] and LEAP[4] [46] models are widely used in energy system analysis and planning; WEAP[5] [47] and MIKE [48] are commonly used models for water system planning; models such as PODIUM[6] [49] are used for water scarcity and food security planning; and LEAM[7] [50] is among the models applied for assessing the impacts of land use change.

The application of these and similar models can provide valuable information and insights into policy issues. However, despite efforts to expand the scope of some of these to include other aspects (e.g. climate change mitigation assessment), they are often not suited to representing all the important elements of multiple connected resource systems that are relevant for integrated policy assessment.

Accordingly, the CLEW framework developed by IAEA together with UN partners and scientific experts goes beyond traditional methodological approaches to resource planning in order to integrate important interactions between resource systems, thereby minimizing the risks of inconsistent planning and policy in which a strategy or policy implemented in one area undermines objectives in another policy area.

3.2. THE CONCEPT OF CLEW

The CLEW framework links different resource assessment approaches and methodologies and facilitates collaboration between climate, land, energy and water experts. By integrating different assessment approaches, the CLEW framework enables the simultaneous consideration of issue relevant to land, energy and water sectors and their impact on, and vulnerability to, climate change.

The flexible CLEW approach builds on existing knowledge and provides a framework to either link separate quantitative modelling tools covering each of the three resources or represent these resource systems in a single tool, with each approach having different strengths and weaknesses (see section 3.3). The approach is complemented with either scenario analysis or additional methodologies representing climate change. Fig. 6 illustrates this concept.

In either case (i.e. representing the CLEW system either by linking separate sectoral models or in a single integrated model), it is important to identify the points at which the resource systems interact and establish appropriate connections or data exchanges between the separate sectoral models or between sub-modules in the single integrated model. These include water requirements in land use and energy systems; energy needs for water supply and land use; and land requirements for energy and water infrastructure and extraction.

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[1] Model for Energy Supply Strategy Alternatives and Their Environmental Impacts
[2] Open-Source energy Modeling System
[3] MARKet ALlocation
[4] Low Emissions Analysis Platform
[5] Water Evaluation and Planning System
[6] Policy Dialogue Model
[7] Land Use Evolution and Impact Assessment Model

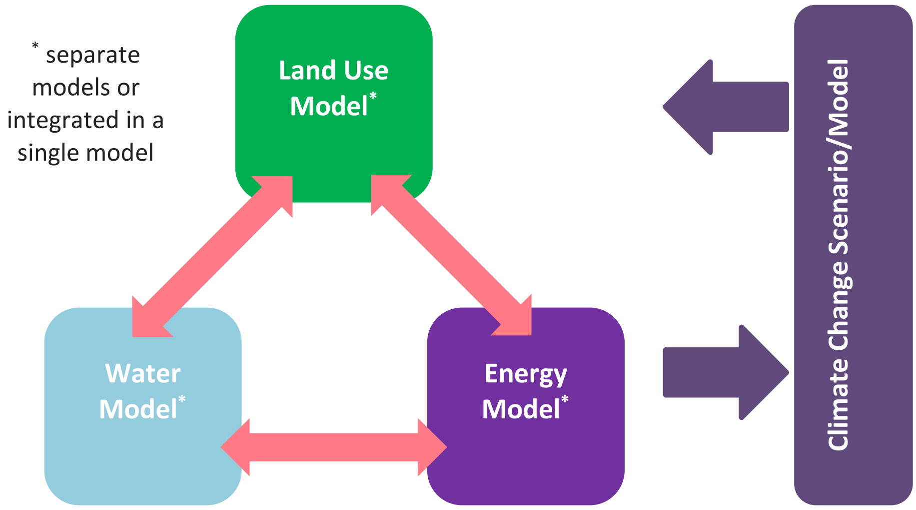


FIG. 6. Conceptual illustration of the integration of different resources assessment tools in the CLEW framework.

In the case where individual models are linked, the output from one model provides the input for the two others, which then are solved sequentially with data then provided to the two other models. The process is repeated through a series of iterations until a convergent solution is found [51]. Inputs to the models (either linked resource models or a single integrated model) also include data reflecting alternative climate change scenarios based on the literature or output from climate models, such as estimates of future temperature, precipitation, evaporation and other parameters.

3.3. ADVANTAGES AND SHORTFALLS OF THE MODULAR APPROACH

The fact that the CLEW framework can be used to build on and integrate previously established modelling methodologies renders it less costly in terms of effort and resources than building a completely new fully integrated model. When applying the framework, the use of existing sectoral models greatly reduces learning curves and allows for better use of already acquired knowledge and experience. Experts from the various disciplines can immediately contribute their established tools and expertise and quickly engage in collaborative work.

At the same time, the modular approach makes it possible to run the individual models independently. In this manner, improvements or updates made to individual models can be readily incorporated during the course of a CLEW study. Furthermore, this allows users to check the impact of the integration by comparing the model behaviour in an integrated mode against a standalone mode.

On the other hand, compared with a fully integrated model, the modular approach is more likely to suffer from inconsistent resource definitions and system boundaries between models, creating challenges in fully accounting for resource flows and linkages. Moreover, different models will likely be maintained and operated by different groups with different priorities, timeframes and resources; aligning the work of these different teams may involve substantial coordination between institutions. The modular approach may also create computational challenges in finding a convergent and optimal solution across the different models.

3.4. OTHER CHALLENGES AND LIMITATIONS OF THE CLEW APPROACH

For either the modular or single-model approaches, there are situations where flows of energy, water and agricultural products cross the geographical boundaries of a CLEW study, leading to potential physical and/or economic knock-on effects outside these boundaries. If the area of the CLEW study or the change in transboundary resource flows is small compared to the overall system, these feedback effects might be negligible and could potentially be ignored. If, on the other hand, they are not, it may be necessary to broaden the geographical scope of the CLEW analysis, apply additional models and analytical methods or adopt a stylized representation to account for feedbacks outside the system boundary.

It should also be recognized that the CLEW framework is not intended to represent or estimate the value of ecosystem services. Thus, the framework is not suited to assessing some impacts: for example, the expansion of agriculture into natural habitats or the adoption of monoculture, along with other management practices, that can have a detrimental impact on biodiversity. While such impacts on biodiversity may have severe long term effects on a wide range of natural ecosystem services, which in turn have effects on freshwater resources, soil health, and climate variability and change, they are beyond the scope of the current CLEW framework.

3.5. AREAS OF APPLICATION OF THE CLEW FRAMEWORK

In addition to mapping key relationships and interlinkages between the land, energy and water domains, as well as their interactions with the climate, the CLEW modelling framework can support [52]:

- **Decision making**: The CLEW framework can be valuable to decision and policy makers in assessing their options in terms of their likely effects on the broad CLEW system and in evaluating the trade-offs revealed in different options.
- **Policy assessments**: In contrast to traditional one dimensional assessment tools, the integrated framework, by providing a more complete, multi-system policy assessment, can help policy makers design comprehensive, multi-objective policies rather than multiple policies focusing on single objectives. This way polices can be as cost effective as possible.
- **Facilitating policy harmonization and integration**: The CLEW approach can bring to the fore potential conflicting and contradictory policy options, thus providing decision makers with the rationale to avoid them. For example, encouraging subsistence farmers to acquire solar irrigation systems through loans can lead to switching to growing cash crops in order to pay off the loans. In these situations, while solar irrigation has positive climatic benefits, abandoning the crops and feed animals used to maintain the farmer and the farmer's family may have negative consequences on food security.
- **Technology assessments**: The CLEW approach allows the assessment of technology options that affect multiple resources. For example, switching from oil based transportation fuels to biofuels can, in many instances, reduce GHG emissions and decrease dependence on energy imports, but it may increase water withdrawals and use, induce large scale land use change and negatively impact food security.

— **Scenario development**: The CLEW framework enables the elaboration of consistent scenarios of possible socioeconomic development trajectories with the purpose of identifying future development opportunities, as well as of understanding the implications of different policies.

4. IMPLEMENTATION OF THE CLEW FRAMEWORK

4.1. SETTING UP A CLEW STUDY

The key phases to conduct a typical CLEW assessment are shown in Fig. 7. The process is sequential, but some overlap and iteration is expected. For example, model building and data collection can be done in parallel, and data shortages may necessitate pre-nexus reassessment.

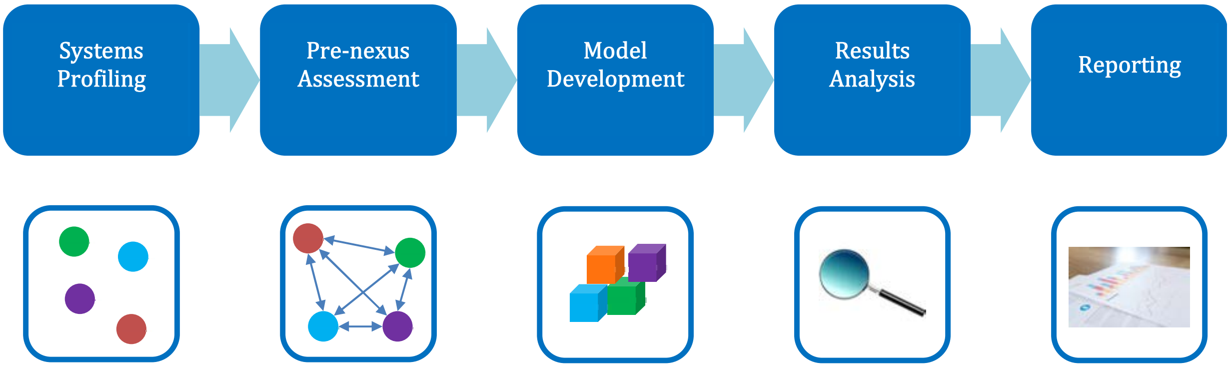


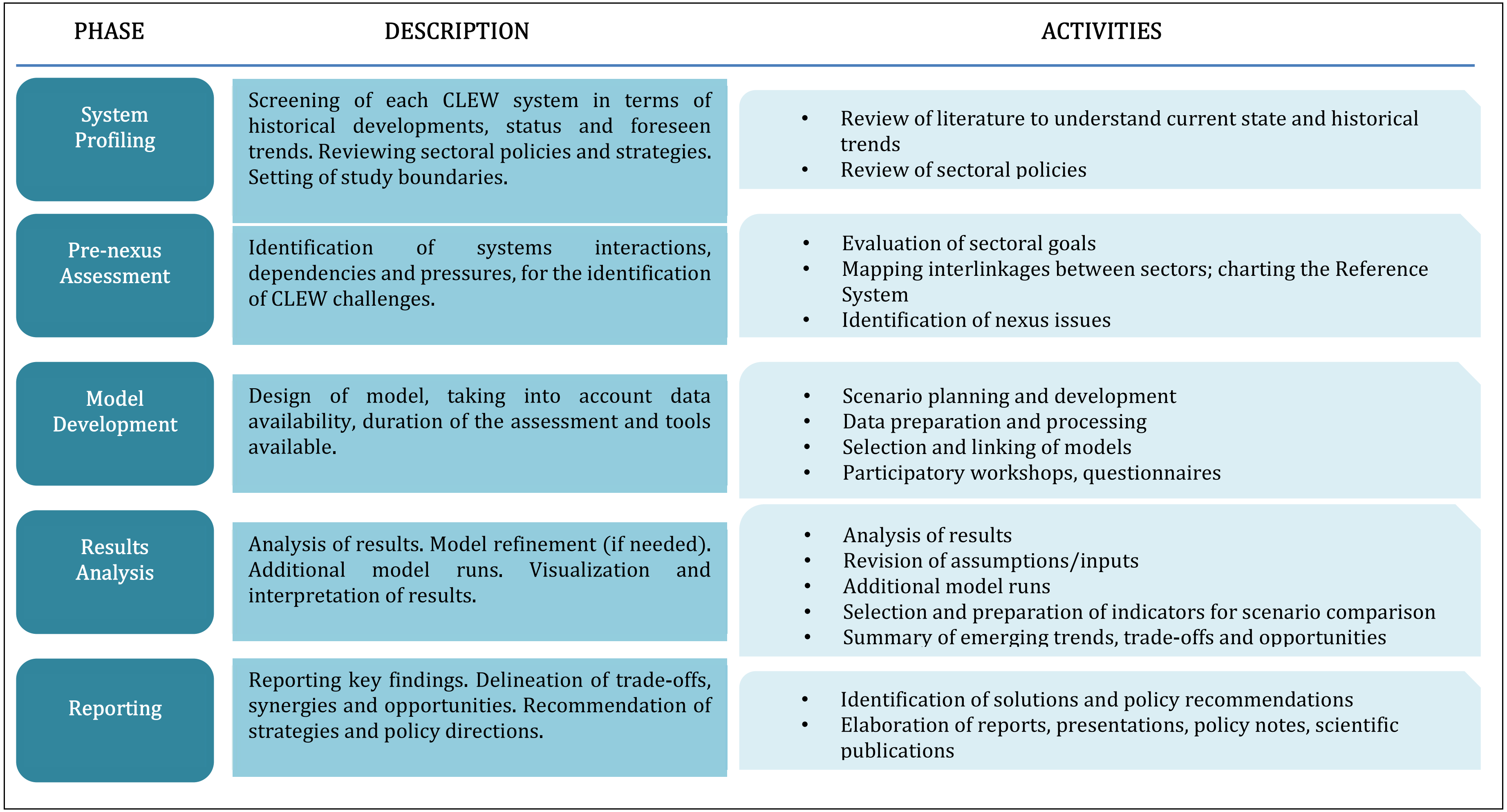
FIG. 7. Key phases in the CLEW approach.

In each phase, specific procedural activities are carried out, as summarized in Fig. 8. The context and purpose of the study influence how the assessment is conducted and the appropriate emphasis placed on each of the phases presented. For example, if the objective of the assessment is to provide options to policy makers, then the involvement of stakeholders in phases such as system profiling and pre-nexus assessment becomes mandatory. Also, if the study is an academic exercise, reporting the results in the form of scientific papers may negate the need for specific actionable policy recommendations.

4.1.1. Systems profiling

The first step in a CLEW assessment is to survey and understand the current situation. Profiling the systems involves forming a comprehensive picture of their characteristics, including identification of key resources, commodities and technologies currently used and those that might be used in the future, and understanding how each functions in the context of the assessment domain. It also includes an assessment of the present state, challenges and outlook for each of the sectors (i.e. energy, land and water). Furthermore, national development policies and strategies need to be identified, at both the sectoral and overarching levels. Of course, the objective of a CLEW study is to adopt an integrated approach rather than focusing on 'silo' perspectives, but it is important to understand the individual systems so that drivers, pressure points and interlinkages, or 'hot spots', among the systems can be identified.

At this stage a consensus needs to be reached among the stakeholders concerning the definition of system and case study boundaries, both geographical and temporal; formulation of the problem; the priorities and the policy objectives.



PHASE	DESCRIPTION	ACTIVITIES
System Profiling	Screening of each CLEW system in terms of historical developments, status and foreseen trends. Reviewing sectoral policies and strategies. Setting of study boundaries.	• Review of literature to understand current state and historical trends • Review of sectoral policies
Pre-nexus Assessment	Identification of systems interactions, dependencies and pressures, for the identification of CLEW challenges.	• Evaluation of sectoral goals • Mapping interlinkages between sectors; charting the Reference System • Identification of nexus issues
Model Development	Design of model, taking into account data availability, duration of the assessment and tools available.	• Scenario planning and development • Data preparation and processing • Selection and linking of models • Participatory workshops, questionnaires
Results Analysis	Analysis of results. Model refinement (if needed). Additional model runs. Visualization and interpretation of results.	• Analysis of results • Revision of assumptions/inputs • Additional model runs • Selection and preparation of indicators for scenario comparison • Summary of emerging trends, trade-offs and opportunities
Reporting	Reporting key findings. Delineation of trade-offs, synergies and opportunities. Recommendation of strategies and policy directions.	• Identification of solutions and policy recommendations • Elaboration of reports, presentations, policy notes, scientific publications

FIG. 8. Phases of a CLEW study. Source: adapted from Refs [53, 54].

4.1.2. Pre-nexus assessment

Following the profiling of the individual of CLEW systems, the identification of existing and potential future interactions in the pre-nexus assessment phase begins.

In this phase, a basic conceptual CLEW reference system (see Section 5) is first established. This is often represented using a resource-to-service block diagram that links together the individual components of the land, water and energy systems in a web of production chains.

The mapping of interactions allows assessment of the dependence between systems and their sectors and the pertinent nexus issues or pressure points. The CLEW reference system diagram can also be useful later for delineating the structure of a CLEW model; that is, it provides a guide for the analytical phase by showing which interactions will have to be represented mathematically.

The pre-nexus assessment phase also provides the opportunity for the first assessment of data requirements and availability. Data on the relevant natural and physical capital including stocks, capacities, technical characteristics and cost information are needed.

This pre-assessment process can also support additional screening and assessment of policy relevant linkages to focus and simplify further analysis and/or modelling. The CLEW reference system may need to be revised in light of this assessment after determining the appropriate scope and level of detail for the CLEW study to support policy needs.

4.1.3. Model development

The next phase is model development. This involves refining the model structure depicted by the CLEW reference system, adapting it to the scope and needs of the study. For each assessment, model design should be determined by the policy questions of interest and issues to be explored. This phase also involves selection of modelling tools and/or quantitative methods and populating the model structure with the data collected during the previous phase. This includes selecting a base year for the model, usually representing the latest year for which a reasonably complete dataset can be assembled.

Furthermore, this phase includes the design and implementation of scenarios to study the CLEW challenges identified in the pre-nexus assessment phase. These scenarios might concern, for example, climate change, demand growth, technological parameters, resource availability and costs, or policy constraints. Scenario development could result in the update of the interactions mapped and/or considered in the analysis.

An important scenario to be developed here is the ‘reference’ or ‘business as usual’ scenario. This is a hypothetical baseline case future that includes the current suite of policies, as well as the plans and strategies likely to be implemented. The calibration of the reference scenario confers robustness to the modelling work, reducing bias to the extent possible.

Next, the model is executed, and its outputs are analysed. This is an iterative process in which the model is successively refined and adjusted until analysts are confident that results are reasonable, robust and consistent. Expert judgement and review often play an important role in this stage, and care needs to be taken to avoid introducing excessive subjectivity into the analysis.

4.1.4. Analysis of the results

Once the model has reached a state where analysts have confidence in the results it produces, stakeholders are consulted to review and suggest changes. A range of scenarios and extensive sensitivity analyses to explore options, risks and uncertainties are usually required to draw robust conclusions and provide useful insights.

Preliminary results might reveal shortcomings in model structure, and analysts might have to revisit the model development phase and make appropriate adjustments. Additionally, new iterations and/or scenario runs may be needed if results are not conclusive or to test further the dynamics of specific interactions.

4.1.5. Reporting

The CLEW analysis and modelling developed in the previous phases is ultimately designed to serve planners and decision makers. The model, once properly calibrated and tested, calculates the resource and service requirements to meet socioeconomic goals under given scenario conditions.

Insights are drawn from the previous phases, and ideas are communicated to inform decision making and policy design. In addition to denoting the trade-offs, opportunities, hotspots and synergies that emerge from the analytical work, reporting to the decision makers normally includes technical or governance solutions and related recommendations.

4.2. MODELING THE CLEW SYSTEMS

As described in Section 3, the CLEW approach recognizes that many development challenges are closely linked to land, water, energy and climate change, and that these challenges and resources are themselves strongly interlinked. The CLEW framework consists of a set of methodologies intended to assess the nexus of food, energy and water in an integrated manner. It aims to inform sector planning, policy and technology decisions by identifying potential trade-offs and exploring synergies in the production and use of the nexus parts in the context of finite and often stressed natural resources assets, and the challenges of climate change. In other words, it seeks to provide answers to key questions such as:

— What investments are needed in infrastructure to meet the demands for food, energy and water and when?
— How should infrastructure be operated to achieve maximum benefit?
— What are the associated resource requirements in one sector for specific supply scenarios in the other two?
— How should limited resources be allocated to various uses?
— How will allocation, operations and operating constraints change if new resource management strategies are introduced?
— What technologies achieve the least cost and most reliable supply systems?
— What are the associated cross-sectoral impacts?
— Which pollutants are emitted and at what levels?
— How do different climate scenarios affect the operation of food, energy and water systems?

Ideally, models can be used to provide quantitative answers to such questions. However, in some cases, insufficient data are available or accessible to conduct quantitative analysis, and qualitative approaches can be followed instead.

The CLEW framework developed by the IAEA and its partners can be applied using different models and modelling approaches. This enables practitioners to build on existing tools and experience, including the IAEA suite of energy modelling tools for sustainable energy development. Among this suite of tools, MESSAGE[8], acquired by the IAEA in 2000, is widely used for medium to long term energy system planning, energy policy analysis and scenario development [55]. In 2008, the IAEA also presented the initial working code of a tool called SoftMESSAGE designed as a Simple, Open, Flexible and Transparent version of MESSAGE [56]. Subsequently this was renamed OSeMOSYS[9] and established as a tool for long run integrated assessment and energy planning [44].

MESSAGE and OSeMOSYS belong to the class of bottom-up energy modelling tools that are well suited to CLEW analysis. The term 'bottom-up' refers to one of two broad approaches used to model and analyse different aspects of the energy system. Bottom-up, or disaggregated, models focus on sectoral and technological details. They seek to model the deployment and use of different technologies and represent in detail their characteristics. For this reason, they are called technology rich models. These features mean that bottom-up models can be used to account for the interactions of different energy technologies and resources with land and water systems in a CLEW analysis. On the other hand, top-down, or aggregate, models provide an economy wide and macroeconomic perspective. They are thus well suited to analysing the economy as a whole and the relations between parts of the economy. However, conventional top-down models lack technological explicitness, making them less suitable for assessing important policy questions related to resource and technology dynamics.

Within the broad class of bottom-up tools, several different types of models exist. For instance, so called accounting models take snapshots of physical flows and energy balances and are particularly useful for building scenarios. Simulation models mimic the energy system and its operation and can consider the decisions of individual players within the system. Lastly, optimization models calculate how an energy system should be configured and run to reach a certain objective.

In optimization models — such as MESSAGE and OSeMOSYS — the objective is normally cost minimization, that is to determine the least cost combination of technologies and resource flows to meet a given energy demand (subject to various constraints), or more technically, the minimization of the total net present value of the system in the coming years. Other objectives could be the minimization of GHG emissions, in which case the optimization process can calculate what energy supply options should be invested in each year and how they should be operated in order to achieve the best (minimum) outcome for GHG emissions. Optimization models are dynamic and calculate how the system evolves over time (e.g. in different years).

Normally, an optimization model implies a number of characteristics:

— Perfect markets and competition: All actors in the system compete freely on the basis of their costs.

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[8] Model for Energy Supply Strategy Alternatives and Their Environmental Impacts

[9] Open-Source energy Modeling System

- Perfect information and perfect foresight: This means that all costs and characteristics of all technologies in the system are perfectly known to the model, now and in the future.
- Rational behaviour: This means that decisions that affect the system are made solely on the basis of cost. Subjective judgement based on perceptions, preferences and biases thus need to be represented by explicit exogenous constraints or other parameters.

Tools like MESSAGE and OSeMOSYS can be used in several ways to support CLEW modelling. They can be used to model the energy sector alone and soft linked to other modelling tools representing water and land use. Alternatively, they can be adapted to model also water and land uses and their interlinkages with the energy system and the climate. This is because these models are sufficiently flexible to represent different supply chains extending from resource extraction to transmission, distribution, and end use demand devices. These models can be readily modified, for example, to incorporate mathematical representations of the technoeconomic description of a water system that include the definition of the categories of the water resource forms considered, the associated technologies that are actually used, the commodities that flow between the components of the supply chain, as well as the water services provided to end users. Bottom-up models allow as many technologies as necessary to be represented in the system, each properly described by its characteristics. A similar adaptation is also possible for the land system and potentially other resources, such as critical materials.

CLEW modelling is intended to analyse sustainable development issues over the long term (i.e. up to several decades). But it is important to bear in mind that the main aim of modelling is to inform and support sound decisions, not to make predictions about the future. These models have only an idealized representation of the subsystems involved and involve assumptions about how these might evolve in the future. The modeller should strive to make these assumptions as realistic and transparent as possible and remain open about the limitations of such models.

In a CLEW assessment work, climate modelling per se is not necessarily required. Instead, existing climate scenarios from a variety of sources (e.g. the Intergovernmental Panel on Climate Change's Sixth Assessment Report [39]) can be used to define parameter inputs to the different components of the CLEW methodology (land, energy and water modelling). These can include information such as temperature and precipitation patterns.

5. THE CLEW REFERENCE SYSTEM

When developing a CLEW model, it is useful to start by laying out a conceptual reference system of the production chains to be represented in the model. Such a reference system is intended to provide a visual representation of the highly complex and interlinked reality in the form of a simplified, manageable and organized model structure. Without this schematic representation it can be difficult to know what is being modelled and to communicate the model and the results of the analysis.

Fig. 9 illustrates a highly simplified example of a CLEW reference system. Here, the complex set of supply chains constituting a real land, energy and water system is translated into a sketch of a few boxes and lines. In this example, the resources of land, energy and water are used through a set of conversion processes to satisfy the demands of a society for food, energy services and drinking water. In Fig. 9, each box represents a physical process or conversion technology linked by lines that represent the flow of commodities to form a supply chain. At the end of each chain is a final demand that represents the wants and needs of society.

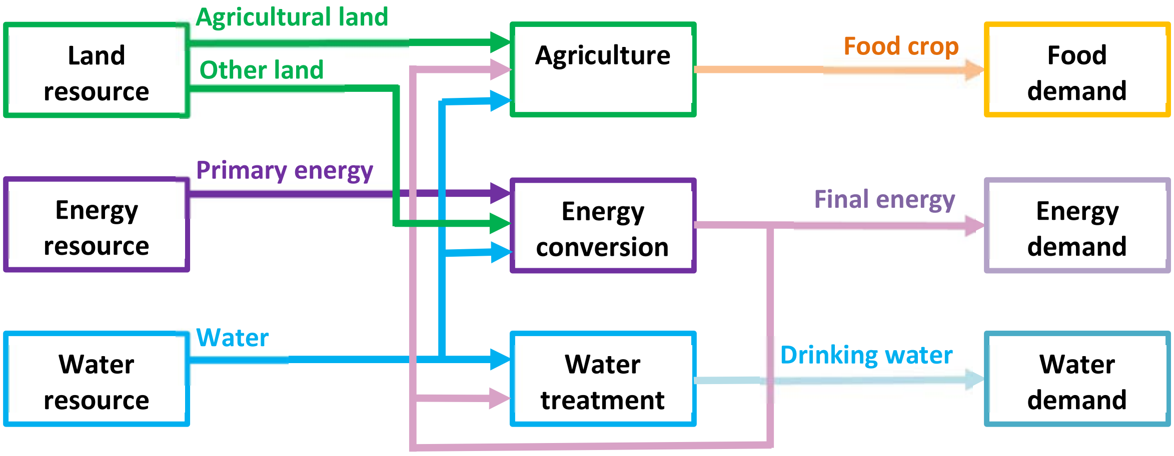

FIG. 9. A highly simplified CLEW reference system.

Generally speaking, the conceptual model structure applies irrespective of whether the analyst intends to link standalone sectoral models (i.e. for each of energy, water and land) — in which case, the CLEW model reference system is split across these models — or integrate all sectors in a single model. Of course, there will be important practical differences in implementation.

The CLEW modelling approach is based on a bottom-up methodology that builds up the whole system by including all the relevant processes. For example, the energy resource block may include coal mining, oil and gas drilling and incident solar radiation. Similarly, water resources may include precipitation, fossil water and surface water. The water treatment block may include water desalination plants. Likewise, the energy conversion block may include coal, gas, nuclear and wind energy power plants, oil refineries and so on. The demand block could be demand for rice, wheat, potatoes, drinking water, irrigation water, cooling water, electricity for home appliances and industrial equipment, or other relevant services or commodities.

The level of complexity of the CLEW reference system depends on the issues that need to be analysed, as well as on the availability of data. For instance, Fig. 10 shows an example energy conversion system that supplies energy in the form of electricity to consumers from the resources of coal, natural gas, wind and solar photovoltaics. In this hypothetical example, the goal is to analyse the relative roles of these sources: thus, it is important to represent the four options separately in the model. Furthermore, it is of interest to compare the advantages of a distributed solar photovoltaic generation system, in the form of rooftop systems against those of grid connected solar photovoltaic power plants. Thus, both systems are included in the CLEW reference system. However, in this hypothetical example there is insufficient data on offshore wind farm performance, so the CLEW reference system does not distinguish between offshore and onshore wind farms.

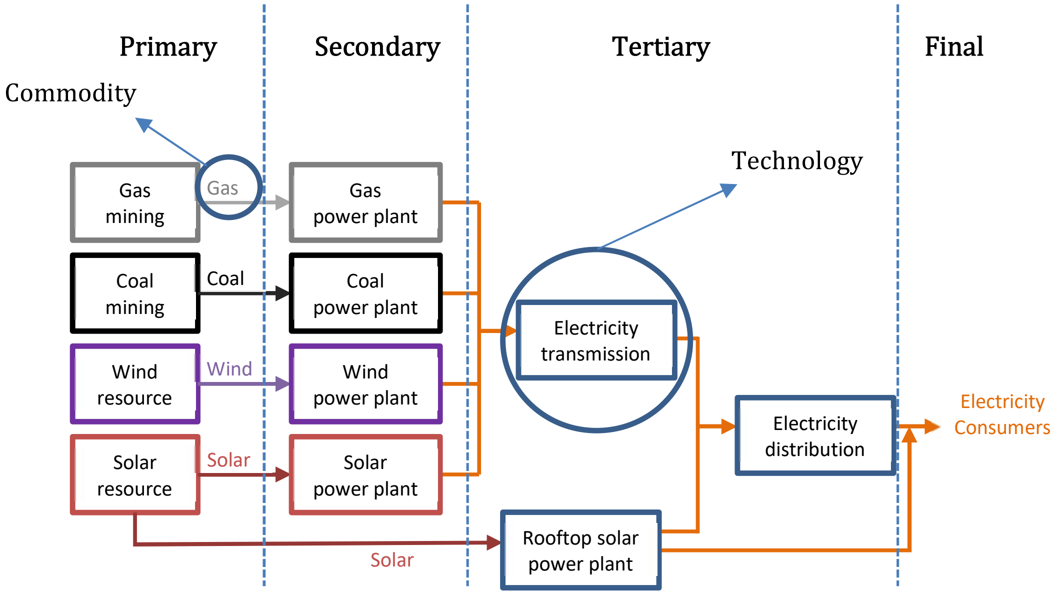

FIG. 10. An example electricity supply system.

Beginning from the left side, Fig. 10 shows the start of the production chain, i.e. the primary resources. These resources (i.e. natural gas, coal, wind and solar radiation) then flow to the secondary level of energy supply, each to its relevant process block, or 'technology'. The output commodity (electricity) from these technologies then flows to the tertiary level of supply which includes the technologies of transmission and distribution. Finally, on the far right, there is the final energy demand.

Each component of land, water or energy systems is described by its technical and economic characteristics. For example, Fig. 11 shows a typical energy conversion process. In this example, a concentrated solar power (CSP) plant uses solar energy to produce electricity and heat. The plant also uses natural gas as an auxiliary source of primary energy when the solar energy is not available (e.g. in cloudy periods or at night). In modelling this power plant, it is described by its efficiency; cost elements, both capital and running; solar fraction, which determines how much auxiliary natural gas is needed; and the spacing needed between solar collectors to ensure proper operation. These process characteristics link the inputs of solar radiation, natural gas, land and water (for cooling) to determine the outputs of electricity and heat.

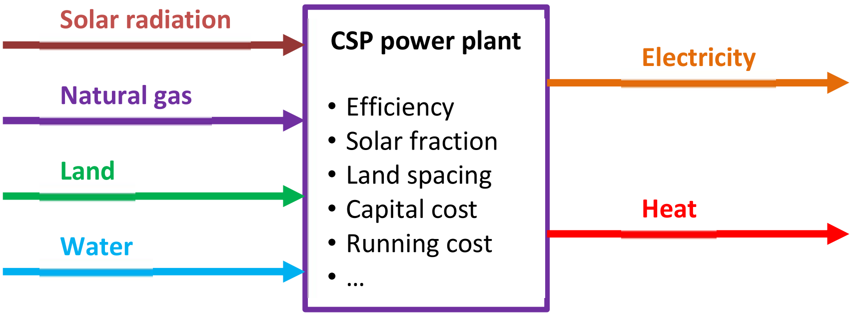

FIG. 11. Representation of a concentrated solar power (CSP) plant with natural gas backup.

In another example, maize farming can be viewed as the process of transforming the resources of land, water and energy to produce maize and other outputs. As illustrated schematically in Fig. 12, the primary resource of total land area is the input to three ‘technologies’ that produce agricultural land, forests and built-up land.

The process of producing maize from agricultural land is controlled by how much maize can be produced from a unit area of agricultural land (i.e. the yield), which depends in part on how water is made available to the growing crop. Therefore, in this example, the commodity of agricultural land flows into the technologies of irrigated land and rainfed land in the tertiary level of the production chain. Both technologies have other inputs in the form of diesel fuel to run farm machinery, natural gas that goes into the manufacture of fertilizers and water.

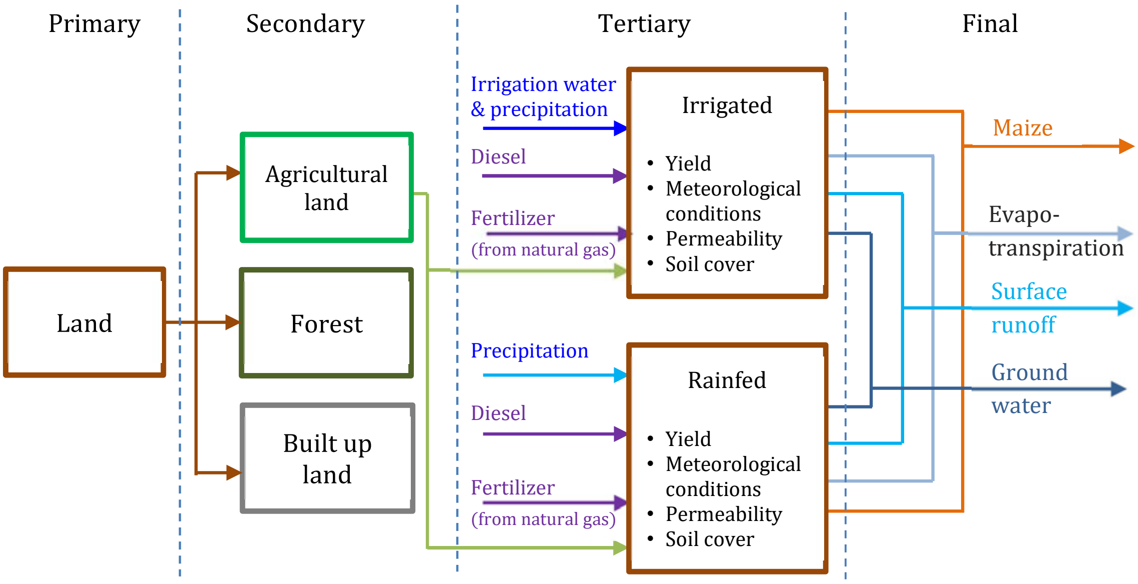

FIG. 12. The production chain of maize production.

In the case of irrigated land, the technology uses both irrigation water and precipitation, while in the case of the rainfed land technology, the water input is in the form of precipitation alone.

The process of producing maize generates other by-products including water that moves to the atmosphere, either through transpiration from the plants or directly through evaporation from the top surface of the soil. In addition, water runs off the ground and/or penetrates it to recharge groundwater reservoirs. These by-products are controlled by the permeability and the type of cover of the soil, as well as the prevalent meteorological conditions.

The CLEW reference system can be made as detailed as needed. For example, in Fig. 12, technologies that describe how the volume of ground water is affected by precipitation and/or surface water flows in forest and built-up lands can be added if this issue is of importance to the analysis. However, it is highly desirable to keep the CLEW reference system as simple as the analysis requires and as the availability of data dictates.

The complete CLEW model involves identifying all the relevant process blocks, or technologies, and describing each by their appropriate technical and economic characteristics. For example, in Fig. 12, technologies that describe the production of diesel fuel and fertilizers from the resources of oil and natural gas, respectively, need to be added. Furthermore, technologies that describe the emission or absorption of GHGs at each of the relevant stages need to also be included in order to account for the impacts of maize production on the climate.

A set of highly interlinked production chains thus emerges in a CLEW model to connect resources and societal demands. The demands themselves are the ultimate drivers of a CLEW model. The model solution is the configuration of the production chains that meets the specified demands (at lowest cost, subject to various constraints). The model solution also shows which infrastructure assets need to be constructed and how they need to be operated in a way that converts the available natural resources to meet demands for commodities and services for a given scenario.

Again, it is worth noting that the concepts and approaches described above apply regardless of whether the analyst is developing a CLEW model by linking standalone sectoral tools or integrating land, energy and water into a single model. However, each modelling approach brings its own challenges in terms of representing intersectoral linkages, ensuring consistency, and technical implementation.

It is also important for the analyst to remain mindful of the limitations of such models. A model solution represents only one possible configuration of the resource system — it is neither predictive nor prescriptive — but by modelling a range of scenarios and conducting extensive sensitivity analysis to explore options, risks and uncertainties the analyst can derive more robust insights to support decision making.

6. CONCLUDING REMARKS ON THE CLEW FRAMEWORK

Linkages between energy, water and land are complex and dynamic, and the interactions between these three sectors are becoming increasingly critical as population growth, urbanization, and economic growth combine to exert even greater pressure on resources. Moreover, as the need to respond to climate change becomes more urgent, climate policies may impact or be impacted by water, energy and land resources.

Within the context of sustainable development, in addressing the daunting challenge of climate change while fulfilling simultaneous demands for food, water and energy in a sustainable manner, ‘silo thinking’ is no longer an option. Energy, water and land need to be looked at as a ‘system’ influenced by climate change. Treating the three sectors in an integrated manner can optimize overall welfare and result in a more optimal allocation of resources, improved economic efficiency, lower environmental and health impacts and better economic development conditions.

A holistic approach explicitly defines the links between the single components of the CLEW nexus and accounts for the effect each one has on the others. Responding to the need for such approaches, the IAEA has developed, in collaboration with UN partners and scientific experts, the integrated CLEW framework with the aim of enabling land, energy and water planning to support broader development policy objectives by assessing how policies in one domain may be complementary to other policy goals, or conversely, how pursuit of policy goals in one domain may be detrimental to the progress in others.

The CLEW framework explores the interactions between the climate, land, energy and water systems and, through quantitative tools, identifies the potential trade-offs and synergies in the production and use of nexus resources. The framework builds on existing knowledge and provides a structure to either integrate separate quantitative modelling tools covering each of the three resources or integrate each of the resources into a single tool.

The implementation of a CLEW study is organized in five key stages: (1) systems profiling; (2) pre-nexus assessment; (3) model development; (4) analysis of results and (5) reporting. The process is sequential, but some overlap and iteration is expected.

A crucial step in implementing the CLEW framework is the establishment of a CLEW reference system. This is a schematic representation that provides a visual impression of the highly complex and interlinked reality in the form of a simplified, manageable and organized model structure. It helps to show what is being modelled and to communicate the model and the results of the analysis to the intended audience.

The level of complexity of the reference system depends on the issues that need to be analysed, as well as on availability of data. Each component of land, water or energy systems shown in the CLEW reference system is described by its technical and economic characteristics. The complete system results in a set of highly interlinked value chains that connects the resources and the societal demands.

Finally, the model solution shows, for a given scenario, which assets would need to be deployed and how they need to be operated to most efficiently convert available natural resources into commodities and services to meet final demands. By modelling a range of scenarios and conducting extensive sensitivity analysis to explore options, risks and uncertainties, these results can help to derive robust insights to support decision making. Nonetheless, it is important to recognize the limitations of such models and ensure these are reflected in the way model results are communicated to decision makers.

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CONTRIBUTORS TO DRAFTING AND REVIEW

Berdellans Escobar, I.	International Atomic Energy Agency
Khartabil, H	International Atomic Energy Agency
Siala, F.	Consultant, Austria
Turton, H.	International Atomic Energy Agency
Welsch, M.	International Atomic Energy Agency

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