Integrated Assessment of Climate, Land, Energy and Water

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INTEGRATED ASSESSMENT OF CLIMATE, LAND, ENERGY AND WATER

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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".

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FOREWORD

At the heart of sustainable development is the goal of satisfying basic human needs, such as energy, food and water, while addressing challenges such as climate change, which can affect the ability of future generations to meet their own needs. The IAEA assists Member States in using nuclear science and technology to meet their development objectives in areas including energy, human health, food production, water management and environmental protection, supporting their efforts to reach the 17 Sustainable Development Goals (SDGs) adopted by the United Nations. In the field of energy, the IAEA's assistance to countries ranges from supporting the efficient and safe use of nuclear power to building capacity in national and regional energy planning to address multiple objectives of sustainable development.

This publication presents the findings of the coordinated research project (CRP) Assessing Interdependencies between Energy, Water, Land Use and Climate Change, which addressed the development and application of an analytical framework for energy planning that enables the integrated assessment of climate, land (including food), energy and water (CLEW). Research teams from ten IAEA Member States participated in the CRP, and the results and analysis presented in the publication are based largely on their diligent work. The wide range of research questions, applied methodologies and analytical results included in the CRP have helped to advance the state of knowledge of linkages between CLEW domains and to establish a solid foundation for further applications of the framework.

This work complements major IAEA activities in capacity building in energy planning, nuclear energy technology development, the sustainable management of agriculture and water resources, and the monitoring of and adaptation to climate change. In energy planning, the CLEW framework expands established IAEA activities strengthening Member States' capacities to elaborate sustainable energy strategies and to conduct studies for electricity supply and energy system options, energy investment planning and energy–environment policy formulation. This includes strategic support for Member States in the integration of energy–environment policy, for example via major events such as the International Ministerial Conference on Nuclear Power in the 21st Century, in Abu Dhabi in 2017, and the International Conference on Climate Change and the Role of Nuclear Power, in Vienna in 2019. In the broader energy domain, the IAEA fosters the efficient and safe use of nuclear power by supporting new and existing nuclear programmes around the world, catalysing innovation and building capacity in nuclear information and knowledge management. This includes initiatives that are directly relevant to CLEW, such as supporting Member States to develop strategies for efficient water management in nuclear power plant construction, commissioning and operation to protect water resources and to ensure a reliable energy supply. Examples include support in identifying and implementing water supply options, such as desalination technologies that can supplement water needs beyond the power plant. In addition, activities indirectly related to CLEW include the development of advanced and innovative nuclear reactor technologies that can serve to meet increasing energy demands in a sustainable manner. Complementary activities outside the energy domain include the Joint FAO/IAEA Programme of Nuclear Techniques in Food and Agriculture, established in 1964, which supports the safe and appropriate use of nuclear and related technologies in food and agriculture so as to contribute to global food security and sustainable agricultural development. Similarly, the IAEA provides Member States with the information and technical skills to understand and manage water resources. Many of these activities also benefit from IAEA support to Member States in monitoring the climate with nuclear and isotopic techniques and improving the resilience of agriculture and water systems to adapt to effects of climate change. In addition to the CLEW framework, these activities also contribute to the effective long term management of key resources for sustainable development.

The IAEA officers responsible for the CRP and this publication were T. Alfstad and H. Turton of the Division of Planning, Information and Knowledge Management.

CONTENTS

1. INTRODUCTION

1.1. BACKGROUND

Climate change and the provision of energy, food and water are among the most important global development challenges faced today. Hundreds of millions of people lack access to basic food and water supplies, and billions lack access to modern forms of energy. At the same time, there is a need to mitigate and adapt to climate change. Supporting Member States in their efforts to address these development challenges closely aligns with the IAEA's mandate, with many Member States applying nuclear techniques for food production, energy, water management and environmental protection.

Critically, development challenges relating to energy, food, water and climate are closely linked: the production of food relies on direct and indirect inputs of energy and water; the provision of clean water requires energy for pumping and treatment; and the energy sector consumes water and biomass from agriculture and forestry. All three are connected to climate change, since energy and land use are the main sources of greenhouse gases (GHGs), while food production, water supply and energy systems (e.g. hydropower) are entirely reliant on a stable climate. Furthermore, energy, water, land use and climate change are also related to other aspects of human and economic development.

Despite these linkages, the assessment and management of resources such as land, energy and water are often conducted in isolation by separate and disconnected agencies, running the risk that important interactions between resource systems may be overlooked or misunderstood. This can lead to less efficient policy design with unintended outcomes, which may be particularly detrimental in countries facing acute challenges relating to climate change and the access to energy, food and water.

This calls for the integrated assessment of these resources to support policy formulation and planning. To respond to this need, a climate, land, energy and water (CLEW) framework has been developed by the IAEA and other United Nations organizations and academic partners. The CLEW framework comprises a set of quantitative tools that can simultaneously assess strategies for the management of land (including food), energy and water resources, while accounting for how the use of these resources can contribute to climate change, as well as how these resource systems are likely to be affected by future changes to the climate. The CLEW methodology is sufficiently flexible to enable its application at global, regional, national and local levels to serve planners and decision makers in conducting policy assessments, policy integration and design, technology assessment and scenario analysis. The CLEW framework complements and extends the IAEA's role in fostering the efficient and safe use of nuclear energy to provide access to clean, reliable and affordable energy by building capacity for the integrated and holistic assessment of energy strategies. This publication illustrates that the flexibility of the CLEW framework makes it suitable both for Member States using (or considering using) nuclear power and for other Member States.

1.2. OBJECTIVE

The objective of this publication is to synthesize the development and application of the CLEW framework, along with specific outputs and findings, from studies conducted by Member States as part of a coordinated research project (CRP) on Assessing Interdependencies between Energy, Water, Land Use and Climate Change.

1.3. SCOPE

This publication compiles and summarizes the development and application of the CLEW framework in the CRP, which sought to improve the understanding of the interdependencies, trade-offs and co-benefits between the CLEW domains. The scope of this publication reflects the objectives of the CRP to expand and improve the knowledge base, tools and toolkits available for the integrated assessment of energy, water, land use and climate change, as well as to demonstrate the applicability of these tools in different countries facing diverse challenges. The CRP research presented helps to identify practical strategies and policies for the coherent development and management of land, energy and water resources, and responses to climate change, despite the preliminary nature of several of the studies.

This publication reports on the work of scientists from research institutions in ten developing and developed countries: Australia, Brazil, Cuba, Germany, India, Lithuania, Mauritius, South Africa, the Syrian Arab Republic and Thailand. The teams applied a range of methodologies to analyse the CLEW challenges in each of their countries, which differ in attributes such as geography and climate, economic development, resource endowments, vulnerability to the impacts of climate change, and policy priorities. Approaches included bottom-up partial equilibrium models and accounting frameworks, and applications of institutional economics and political economy, among others. The wide range of problems and challenges addressed and the array of methodologies applied has helped to advance the state of knowledge of CLEW and to establish a solid foundation for future applications and studies. Guidance provided here, describing good practices, represents expert opinion but does not constitute recommendations made on the basis of a consensus of Member States.

1.4. STRUCTURE

Section 2 outlines the main challenges for sustainable development and the interlinkages between climate change, energy and water, along with the rationale for integrated assessment and features of the CLEW methodology. Section 3 presents an integrated summary of the country analyses conducted in the CRP, synthesizing individual country findings across different axes of the CLEW nexus (e.g. interdependencies between energy–water, water–climate, and so on) to ultimately address interdependencies, trade-offs and co-benefits integrating across all domains. Section 4 summarizes the findings and conclusions from the CRP, including the lessons identified with respect to the application of the CLEW methodology and areas for potential improvements, and the role of capacity building for its successful implementation.

Appendix I summarizes the development of the CLEW framework and the role of the IAEA. Appendix II provides more detail on the individual country analyses, including country background, methodology and scenarios, and selected findings and conclusions.

2. CLIMATE, LAND, ENERGY AND WATER

2.1. CHALLENGES AND INTERDEPENDENCIES IN SUSTAINABLE DEVELOPMENT

Climate change and the provision of energy, food and water represent critical global development challenges. Over 800 million people are currently undernourished, with a similar number malnourished [1]. Furthermore, around 850 million people lack access to a basic water service, with an additional 1.3 billion spending up to thirty minutes to collect water from an improved source outside their homes [2]. Around 2.3 billion also lack access to basic sanitation services [2]. Similar challenges exist in energy access, with close to one billion people still lacking access to electricity and over 40% of the global population lacking access to modern fuels for cooking [3]. The prospects for addressing energy, food and water needs while simultaneously adapting to and mitigating climate change to keep the increase in global temperatures well below 2°C remain highly challenging [4].

While each of these development needs is individually challenging, additional complexity exists because the resource systems supporting the production of energy, food and water are highly interlinked. For instance, around 70% of global water withdrawals are for agriculture (with higher proportions in some countries), and another 19% is used in industrial processes, such as cooling thermal power plants.[1] At the same time, water delivery, transport and treatment, together with sanitation, are significant consumers of energy, accounting for an estimated 4% of global electricity consumption in 2014, and up to 10% in India and the Middle East, where energy intensive water desalination is expected to drive increasing demand in the coming decades [5, 6]. Land is increasingly used to grow feedstocks for energy (biofuel) production, which accounted for around one third of the increase in global demand for maize and oil seeds for 2006–2016 and now consumes around 15% of these crops [7]. Equally, 4–5% of global final energy is used for crop production alone (including fertilizer production, land preparation and harvesting but excluding processing). Taking into account the entire food production chain (production, processing, transport and distribution, wholesaling and retailing, preparation), this increases to 30% of global energy consumption [8]. This highly interlinked land–energy–water system contributes to and is affected by climate change: the energy system and land use are the largest sources of GHG emissions, while changes to precipitation, temperatures and extreme weather events affect agricultural, energy and water systems [4].

The significance of these linkages between climate, land, energy and water is likely to increase with growing demands for resources. Moreover, policy interventions targeted at one of these domains could have impacts on other areas. Such impacts could be detrimental (e.g. biofuel policies compromising food and water security) or they could be beneficial (e.g. water efficiency measures reducing electricity demand for water pumping, in turn reducing power plant cooling water requirements) depending on the choice of technologies for supplying demands for energy, food and water. Using the energy sector as an example, the impacts of electricity generation on water usage, GHG emissions and land requirements vary substantially across technologies [9]. Electricity generation from coal produces the highest GHG emissions per unit of electricity and occupies a relatively large land area for mining. In comparison, nuclear power has among the lowest GHG emissions and land requirements per unit of electricity but requires similar amounts of water to other thermal electricity generation technologies. Among other low carbon options, solar and wind power have higher land requirements and can be less suited to providing the reliable

[1] See www.fao.org/aquastat/en/overview/methodology/water-use

electricity supply required for sustainable development; while hydropower requires significant amounts of water and, in many cases, also occupies large areas of land. Similar variations in land, energy and water requirements, and GHG emissions, exist in food production (e.g. depending on crop selection, fertilizer inputs, tillage, mechanization and irrigation) and water supply (e.g. depending on catchment and reservoir management, resource characteristics and extraction methods, particularly desalination, and distribution) [5, 8].

2.1.1. Agenda 2030 and sustainable land, energy and water use and climate change action

Interlinkages between the pillars of sustainable development [10] have long been recognized and extensively discussed in the literature, including: their nature and magnitude; impacts on one another; the need for (and lack of) integrated planning; and how to quantify the links and represent interdependencies in planning and policy assessment.

The myriad interlinkages and interdependencies between energy, food and water are considered to be at the heart of the sustainable development challenge, since these resources provide the very basis for human survival. These interdependent challenges also affect numerous other socioeconomic and environmental aspects of sustainable development. For example, access to energy, food and water is fundamental to reducing the effects of poverty and to improving health and well being. Access to energy is linked to the provision of education, gender equality, industrial and economic development, and sustainable consumption and production. The production of food, water and energy rely on the extraction of resources from (and disposal of wastes to) the environment, so all are intimately linked to ecosystem health.

The importance and complexity of interlinkages have been fully expressed in the 2030 Agenda for Sustainable Development, adopted by the United Nations [11]. The 2030 Agenda seeks explicitly to address interlinkages between 17 Sustainable Development Goals (SDGs) and 169 targets by recognizing their integral nature and indivisibility (see Fig. 1). Nonetheless, planners and policy makers are confronted with the conundrum that: (i) SDGs and targets may be synergistic and thus reinforce one another; (ii) they may be symbiotic and depend on one another; and (iii) they may even be antagonistic; that is, targets imposing constraints on one another to the point of being mutually exclusive and requiring trade-offs, for example competition for fresh water needed for food production (SDG 2), clean water and sanitation (SDG 6), energy (SDG 7), industry (SDG 9) and ecosystem protection (SDG 15) [11, 12].

FIG. 1. The Sustainable Development Goals.

2.1.2. Traditional approaches to assessing climate, land, energy and water

The linkages between energy, water, land use and climate change, along with their relationship to sustainable development underscore the need to assess policy and planning decisions relating to these resources in a systematic, integrated manner. While integrated environmental assessments are routinely 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. For instance, conventional approaches to the management of a single resource (e.g. water) generally treat other resource inputs (e.g. energy) and demand as external to the resource system (see Ref. [13] for additional background, including relatively recent efforts to apply more inclusive approaches).

In comparison, the IAEA [14] has sought to encourage the development of stylized general approaches to assessment that focus on the national level, building on and integrating existing knowledge and approaches.

2.1.3. The need for integrated assessment and capacity building

Traditional approaches to resource management run the risk of overlooking or misunderstanding important interactions between resource systems. In turn, this could lead to inconsistent planning and policy in which a strategy or policy implemented in one area undermines objectives in another policy area [13]:

> “For instance, the strong drive by many governments to promote biofuels… did not foresee the full impact of rapid biofuel expansion on land and food markets, nor the potentially adverse consequences of land-use change associated with the expansion of biofuel production on the emissions of greenhouse gases”.

In other words, a policy aimed at promoting biofuels to reduce GHG emissions may have, perversely, increased GHG emissions. In comparison, more integrated assessment approaches that look across resource systems, such as the CLEW framework, aim to identify these unintended interactions, thereby enabling policy makers to anticipate and adopt additional safeguards or, even better, to develop alternative policies with positive synergies across resource systems.

Ideally, integrated assessment methods also need to capture the impact of climate change on the agricultural, water supply and energy sectors to support robust longer term planning that addresses not only interactions between these resources but also potential trade-offs and synergies between long term climate change mitigation and adaptation.

While all countries face challenges relating to the land–energy–water nexus, these are often most acute in developing countries, in which significant proportions of the population may lack access to energy, food and water. Such countries may also be particularly vulnerable to the impacts of climate change, due to a combination of geography, poverty and related infrastructure deficits. Accordingly, implementing nexus thinking and integrated assessment has the potential to contribute significantly to sustainable development in developing countries. In many cases, however, developing countries may not have as extensively developed policy and planning institutions as higher income countries, reducing their capacity to effectively address longer term integrated development needs or to establish linkages between different government agencies tasked with water, land and food, and energy management.

Accordingly, there exists a potential need for support in developing capacity in developing countries to undertake national and subnational integrated assessments of the CLEW nexus. Such capacity development clearly must be compatible with local policy and planning needs, institutional and analytical infrastructure, and personnel; that is, developing countries are likely to benefit most from integrated planning methodologies that are suited to domestic policy questions and can be used, developed and maintained locally.

2.2. INTEGRATED CLEW FRAMEWORK

Given the critical importance of production and use of energy, food and water to sustainable development and the interlinkages between each of these domains, there is a need for an integrated assessment methodology to support policy formulation and planning for these resources, particularly in developing countries. Moreover, given that these domains are also affected by current and future climate change impacts, such an integrated methodology must necessarily account for linkages with climate, supporting policy making and planning for both adaptation and mitigation.

To respond to this need, the integrated CLEW framework has been developed by the IAEA and its partners (see Appendix I). The CLEW framework comprises a set of quantitative tools that can simultaneously address issues pertaining to energy, food and water, while accounting for how the use of these resources impacts the climate and how changes to climate can affect these resources. The aim is to enable land, energy and water planning to support broader development policy 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 (i.e. to explore trade-offs and synergies).

The basic idea underpinning the CLEW framework is that any assessment of land, energy and water resource systems needs to account for the high degree of integration between these resources; furthermore, the pervasive effects of climate change should also be reflected in any assessment. The CLEW approach builds on and links existing independent assessment methodologies (i.e. quantitative modelling tools) for each of the three resources, complemented with either scenario analysis or additional methodologies representing climate change. With this modular approach, data representing key points of interaction between each resource system (e.g. water requirements in the land use and energy systems, energy needs for water supply and land use, land requirements for energy and water provision) are systematically exchanged between individual sectoral models in an iterative fashion. In other words, output from each model provides input for the other models (see Fig. 2), with each model applied sequentially: for example, the energy system planning model is solved to determine the optimal energy system configuration, and the associated demands for water and bioenergy. The bioenergy requirements are then used as inputs to the land use model, which is solved to estimate water and energy requirements associated with agriculture and land use. These water requirements, together with water needs estimated by the energy model, are then used as inputs to the water model, which estimates the energy requirements associated with the provision of water. In turn, the energy needs determined by the water and land models are then fed back to the energy model, and the process is repeated through a series of iterations until a convergent solution is found.

Inputs to the models 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. The data can be used to calibrate water and land use models and to estimate future energy demands (e.g. for space cooling and heating), thermal power plant efficiencies and electricity transmission losses. This enables the CLEW framework simultaneously to explore both the relationships and interdependencies between

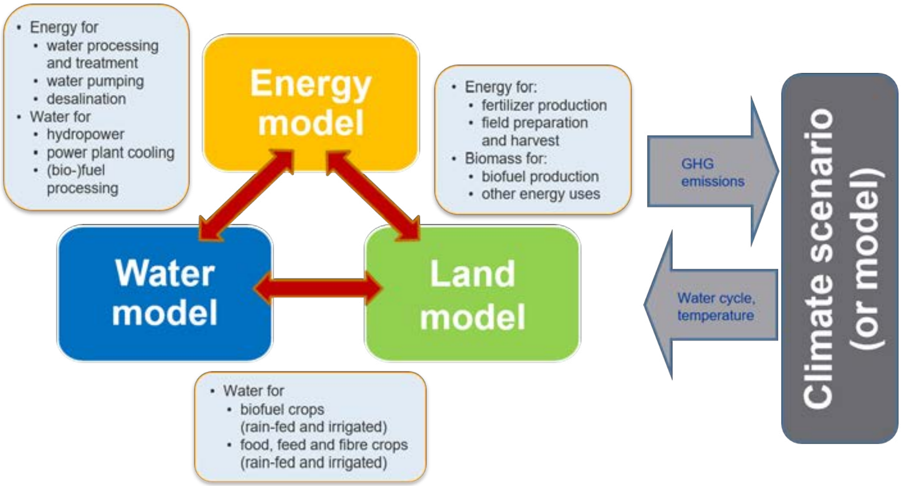

FIG. 2. Integrated CLEW assessment modelling framework. Source: fig. 1 of Ref. [13].

the land–energy–water resource system and trade-offs and co-benefits associated with climate change mitigation and adaptation strategies.

As briefly mentioned above, the CLEW approach takes advantage of established modelling methodologies, thereby reducing the time and resources required before the framework can be applied, compared with developing a new integrated methodology from scratch. Together with the modular approach, this avoids long learning times, makes better use of existing expertise, and facilitates more rapid and effective cooperation between experts from the land, energy and water domains. Departments, ministries and institutions can readily collaborate, with participants contributing with their established tools and expertise. An additional benefit of the modular approach in the CLEW framework is that the individual methodologies can still be applied separately. This enables users to easily compare model behaviour and results in the integrated CLEW framework against stand-alone model operation. It also reduces the number of models and model versions a user needs to maintain and update.

Despite the advantages of the CLEW framework, the methodology may be less suitable for cases in which substantial resource flows exist beyond the system boundary of the CLEW analysis. For example, changes to patterns of resource use in regions that import or export water, energy or agricultural commodities can have knock-on effects outside the region (both physical and economic). If the transboundary resource flows are small compared to the overall system, these feedback effects might be negligible; on the other hand, the effects may be substantial for more integrated neighbouring regions that share resources (e.g. a river basin). In such cases, it may be necessary to broaden the geographical scope of the CLEW analysis, apply additional models and analytical methods or to adopt a stylized representation to account for feedbacks outside the system boundary.

Although the CLEW framework represents an important step forward for practical integrated systematic analysis, it should be recognized that several issues remain beyond the scope of the current evolving framework. One notable limitation is the exclusion of ecosystem services in the CLEW framework, which makes it difficult to assess the impact on key sustainability indicators, such as biodiversity, of land and water use changes — for instance, expansion of agriculture into natural habitats or the adoption of monoculture. Negative impacts on biodiversity can undermine natural ecosystem services, which in turn can affect water resources, soil health, and climate variability and change [15]. Representing these and other important interwoven systems and resources in the CLEW framework is one of several future development options.

2.2.1. Potential applications of the integrated CLEW framework

The CLEW modelling architecture is designed to serve planners and decision makers in developing effective policies and strategies. The methodology is sufficiently flexible to enable applications at global, regional, national and subnational scales (examples of the latter include assessments at a provincial, catchment or city scale). As outlined in Ref. [16], specific applications can include support for:

(a) Decision making: Assess options in terms of their likely effects on the broad CLEW system and evaluate the trade-offs associated with different options.
(b) Policy assessments: Ensure that policies are cost effective, particularly if multiple objectives can be achieved by a comprehensive policy rather than policies focused separately on single objectives.
(c) Policy harmonization and integration: Identify and avoid conflicting and contradictory policies (e.g. electricity subsidies that accelerate aquifer depletion, which in turn leads to greater electricity use and subsidy requirements).
(d) Technology assessments: Assess the impact of technologies on multiple resources, for example a switch from fossil fuel generation to hydropower could reduce GHG emissions, local pollution and cooling water requirements, but increase (domestic) land use and have a varied impact on water availability.
(e) Scenario development: Elaborate consistent scenarios of socioeconomic development and implications for the CLEW framework for identifying robust development opportunities.

The CRP studies described in this publication illustrate some of the possible applications of the CLEW framework. They also illustrate its applicability across countries in different phases of development, confronting diverse resource challenges and policy questions. Furthermore, the CRP studies demonstrate applications of the CLEW framework across different geographic scales (from national assessments of large countries down to regional and city level studies).

3. INTEGRATED SYNTHESIS OF COUNTRY PROJECTS

The research teams in the CRP analysed a wide range of CLEW related policy issues. This section presents an integrated synthesis of the individual studies, covering methodology, representation of CLEW linkages and findings across different axes of the CLEW nexus (e.g. interdependencies along the energy–water axis, the water–climate axis, and so on). Table 1 lists the participating countries, their study report titles, the main policy focus and the CLEW linkages represented. Of the ten country research teams participating in the CRP, six submitted final reports on the application of the CLEW framework. One of the remaining country teams submitted an advanced intermediate report and other material with a similar level of detail as the other final reports. Furthermore, one research team presented a report on a conceptual methodology for measuring progress towards sustainability in place of a CLEW analysis (Germany). Appendix II provides more detail on the individual country analyses, including country background, methodology and scenarios, and selected findings and conclusions.

TABLE 1. DETAILS OF COUNTRIES PARTICIPATING IN THE CRP

	Study report title	Main policy focus (and CLEW linkages)
Brazil	Impacts of Biofuels Production on Water Resources: Case Study of Ethanol Production from Sugarcane in the Paranaíba Hydrographic Basin	Biofuels (climate–water)
Cuba	Case Studies to Analyze Climate, Land, Energy, Water (CLEW) Interactions in Cuba	Energy–biomass (climate–energy–water)

TABLE 1. DETAILS OF COUNTRIES PARTICIPATING IN THE CRP (cont.)

	Study report title	Main policy focus (and CLEW linkages)
Germany	Integrated Assessment of Climate Impact, Energy and Water Use in Germany against the Background of the UN Green Economy Model and Germany's Sustainability Strategy	Conceptual/methodological
Lithuania	Assessment of Perspectives for Broader Use of Renewable Energy Sources in Lithuania Taking into Account Interdependencies among Energy Water and Climate Change	Energy–biomass (land–energy–water)
Mauritius	Mauritius—CLEW Case Study: Assessing Interdependencies among Energy, Water, Land-Use and Climate Change in Mauritius	Biofuels (climate–land–energy–water)
South Africa	Climate, Land, Energy and Water Strategies in the City of Cape Town	Water (climate–energy–water)
Syrian Arab Republic	The Impact of Environment, Water Resources and Land Protection on the Development of Syrian Energy Supply Strategy	Energy–water (climate–energy–water)
Thailand	Climate–Energy–Water–Land Linkages for Thailand	Biofuels (land–energy–water)

Note: No reports available for Australia and India.

3.1. BROAD COUNTRY SITUATION ASSESSMENT

The countries participating in the CRP vary in terms of geography and climate, economic development, resource endowments and contribution to climate change (see Table 2). Based on 2014 data, the countries fall into lower middle, upper middle and high income groups, range from small to large in terms of population (from 1.3 million to 1.3 billion), with access to modern energy

TABLE 2. SELECTED INDICATORS FOR COUNTRIES PARTICIPATING IN THE CRP, 2014

	Australia	Brazil	Cuba	Germany	India	Lithuania	Mauritius	South Africa	Syrian Arab Republic	Thailand
Population (million)	23.5	204.2	11.4	81.0	1 293.9	2.9	1.3	54.1	19.2	68.4
Income level	High	Upper middle	Upper middle	High	Lower middle	High	Upper middle	Upper middle	Lower middle	Upper middle
Main climate types	Tropical Subtropical Arid Temperate		Tropical	Temperate	Tropical Subtropical Arid Mountain	Temperate	Tropical	Subtropical Temperate	Arid/desert Mediterranean	Tropical
CO_2 emissions (t/capita)	15.4	2.6	3.0	8.9	1.7	4.4	3.4	9.0	1.6	4.6
Arable land (ha/capita)	2.00	0.39	0.27	0.15	0.12	0.80	0.06	0.23	0.24	0.25
Electricity consumption (kW·h/capita)	10 078	2 601	1 434	7 035	806	3 821	2 183	4 229	950	2 540
Annual freshwater withdrawals (% resources)	4	1	18	31	53	4	26	35	235	26
Policy focus of CRP study	NR	Biofuels	Energy (biomass)	Conceptual only	NR	Energy (biomass)	Biofuels	Water	Energy–water	Biofuels

Source: See http://data.worldbank.org/data-catalog/world-development-indicators
Note: Shading indicates high (green), moderate (yellow) or low (red) land, energy and water resource access and availability or, in the case of CO_2 emissions per capita, low (green), moderate (yellow) or high (red) emissions. CRP — coordinated research project; NR — no final report.

varying from limited to universal, and with per capita CO_2 emissions in the range of under 2 tonnes to 15 tonnes. Climate types range from arid and desert climates with around 250 mm precipitation per year to tropical climates with over 2000 mm per year. In addition to the variation across countries, there is further variation within each country across different regions. Two participants in the CRP (Brazil, South Africa) focused on a specific subregion with distinct characteristics.

Given the variety of conditions, the participating countries face a diverse range of CLEW resource policy and planning challenges, which is reflected in the issues addressed in each of the CRP studies and the applied methodologies. This diversity is ideal for testing the flexibility of the CLEW framework and for identifying the suitability of the framework to specific policy and planning challenges, along with areas for further development. On the other hand, this diversity also means that resource interactions are not necessarily represented uniformly across the studies, and thus the integrated summary of results presented in this section is not intended to provide a comparative cross-country analysis.

3.2. COMPARISON OF METHODOLOGIES

A range of methodologies were applied in the CRP studies (see Table 3). Energy production and use were analysed in six of the studies with energy system models including the Model for Energy Supply Strategy Alternatives and their General Environmental Impacts (MESSAGE) [17] and the Long-range Energy Alternatives Planning (LEAP) system [18], along with the Cape Town Water Energy System Analysis Tool (WESAT) model, which is partly based on LEAP (see Appendix II, Section II.6). While there are important differences between these tools, MESSAGE and LEAP both track energy consumption, production and resource extraction across the economy, and are applied to assess future scenarios of energy system development. The Model for Analysis of Energy Demand (MAED) was also used in some studies to estimate future energy demands [19].

Land use was modelled in three studies, using either the (Global) Agroecological Zones ((G)AEZ) methodology [20] or by including a representation of agriculture and forestry in MESSAGE. The (G)AEZ model combines detailed spatial data on climate, soil and terrain conditions to analyse alternative uses of land, water and technology for food and energy production.

Seven studies sought to model water use using several different tools. Three studies applied (or planned to apply, given sufficient data) the CROPWAT model, which assesses water use and irrigation requirements for agriculture based on soil, climate and crop data [21]. This tool can be used in conjunction with the CLIMWAT database of agroclimatic variables for 5000 locations worldwide [22].

TABLE 3. APPLIED METHODOLOGIES AND SCENARIOS IN CRP COUNTRY STUDIES

	Policy focus	Scenarios (including CC)	Energy model	Land model	Water model	Comments
Brazil	Biofuels	3 (with CC; sugarcane expansion)	n.a.	n.a.	CROPWAT/ CLIMWAT	Effectively water only
Cuba	Energy (biomass)	2 (with and without CC)	MAED/ MESSAGE	n.a.	n.a. (CROPWAT — lack of data)	Effectively energy only
Lithuania	Energy (biomass)	2 (medium and high renewable targets)	MESSAGE	Land use (incl. forestry, agriculture), along with water use for energy, was included in MESSAGE Water use for agriculture was not implemented		
Mauritius	Biofuels	6+ (with and without CC; biofuel options)	LEAP	(G)AEZ	WEAP	
South Africa	Water	23 (with and without CC; water demand, treatment, management)	WESAT	n.a.	WESAT/ SAPWAT	WESAT is based on LEAP and WEAP

TABLE 3. APPLIED METHODOLOGIES AND SCENARIOS IN CRP COUNTRY STUDIES (cont.)

	Policy focus	Scenarios (including CC)	Energy model	Land model	Water model	Comments
Syrian Arab Republic	Energy–water	6+ (carbon price; water price; desalination)	MAED/ MESSAGE	n.a.	MAWD	Limited comparability of carbon price scenarios
Thailand	Biofuels	5 (biofuel options)	LEAP	(G)AEZ	CROPWAT/ CLIMWAT	Limited scenario comparability

Note: CC — climate change; (G)AEZ — (Global) Agroecological Zones; LEAP — Long-range Energy Alternatives Planning; MAED — Model for Analysis of Energy Demand; MAWD — Model for the Analysis of Water Demand; MESSAGE — Model for Energy Supply Strategy Alternatives and their General Environmental Impacts; n.a.: not applicable; SAPWAT — South African Procedure for Estimating Irrigation Water Requirements; WEAP — Water Evaluation and Planning System; WESAT — Cape Town Water Energy System Analysis Tool.

Other water models used include the Water Evaluation and Planning System (WEAP) model [23] and the WEAP based WESAT model (also based on LEAP; see Appendix II, Section II.6). WEAP models the water supply and demand balance, water quality and environmental constraints, and can be used to simulate future water system development. The Cape Town study also applied the South African Procedure for Estimating Irrigation Water Requirements (SAPWAT) model [24], which is similar to CROPWAT. The Model for the Analysis of Water Demand (MAWD) model was used in one study (for the Syrian Arab Republic) to project future water demands based on macroeconomic drivers and assumptions related to irrigation, losses and technology. Finally, the modelling of water consumption in agriculture in MESSAGE was elaborated but not implemented in the CRP study by the research team for Lithuania.

Several studies analysed the impact of climate change by applying climate change scenarios developed by the Intergovernmental Panel on Climate Change (IPCC). However, this did not require any climate change modelling to be carried out by the teams themselves, although the Providing Regional Climates for Impacts Studies (PRECIS) model [25] was used in the Cuba study to downscale global climate change patterns to the Caribbean region.

The selection of models used in each study shown in Table 3 reflects the main policy issues and CLEW linkages listed in the last column of Table 1. As shown in Table 3, two studies applied models covering only one of the CLEW resource domains. The Cuba study applied only an energy model, since it was not possible to realize the goal of modelling the water sector. Similarly, the Brazil study applied only a water model. Other studies modelled at least two resources in the CLEW nexus and, as such, were potentially able to analyse resource linkages in additional detail as synthesized in Section 3.3.

3.3. SYNTHESIS OF BILATERAL CLEW LINKAGES

This section outlines the representation of CLEW linkages and synthesizes the main findings across the CRP studies. The main insights are presented in turn for each resource pair or climate connection of the CLEW nexus — for example, the energy–water resource pair or the climate–land connection.

3.3.1. Energy–water linkages

Linkages between energy and water include water withdrawal and consumption for energy production (‘water for energy’) and energy used in the extraction, delivery and treatment of water (‘energy for water’). Multiple studies identified and analysed linkages between these two resources (see Table 3), with five studies applying both energy and water modelling tools; the two remaining studies also acknowledged the importance of these linkages.

3.3.1.1. Water for energy

Along the ‘water for energy’ axis, the Brazil, Mauritius and Thailand studies examined the impact of expanded biofuel production on water withdrawals and consumption. Across these countries, biofuel expansion plans are driven by government policy aimed at displacing petroleum imports, expanding the biofuel export industry, reducing CO_2 emissions or adapting to changing market conditions for traditional crops. As expected, the studies show that the expansion of biofuel production has implications for water consumption, potentially leading to reduced water availability, increased water use conflicts and degradation of water resources. The Brazil study focused on the impacts of increased biofuel production in a single river basin, the Paranaíba River Basin, unlike the national analysis in the Mauritius and Thailand studies. Figure 3 shows water withdrawals for the Paranaíba River Basin in 2010 and future projections under alternative scenarios of sugarcane cultivation for ethanol production. The study illustrates how even countries with abundant water resources (see Table 2) can face critical water impairment from excessive withdrawals for biofuel production in more arid regions, with withdrawals reaching 70–100% of authorized flows in 2021, as shown in Fig. 3. Furthermore, the study illustrates the importance of selecting appropriate basins and zones for biofuel crop cultivation. A related factor affecting water use for biofuel energy production is crop selection, which was examined in the Thailand and Mauritius studies. The Thailand study considered biofuel crop suitability and water requirements across different regions, for ethanol (from sugarcane and cassava) and biodiesel (from oil palm and jatropha). The Mauritius study also considered first and second generation ethanol (from sugarcane and bagasse, respectively). Together, these studies highlight the importance of regional water availability, regional variations in biofuel crop yields (t/ha) and water needs (m^3/ha), among a range of factors affecting energy–water linkages for biofuel production.

In addition to the direct effects on water use, the Mauritius and Thailand studies also considered how increased water use for energy production in turn requires additional energy for water extraction and irrigation (see Section 3.3.1.2).

Some of the studies addressed a second ‘water for energy’ linkage relating to water used in electricity production. This includes water for hydroelectricity generation and water used in cooling thermal power plants. While hydroelectricity was only discussed briefly in most reports, the study from the Syrian Arab Republic paid particular attention to fossil fuel and nuclear power plant cooling water demands, motivated by limited water availability and expected future growth in electricity demand. Figure 4 shows a tenfold increase in water withdrawals for

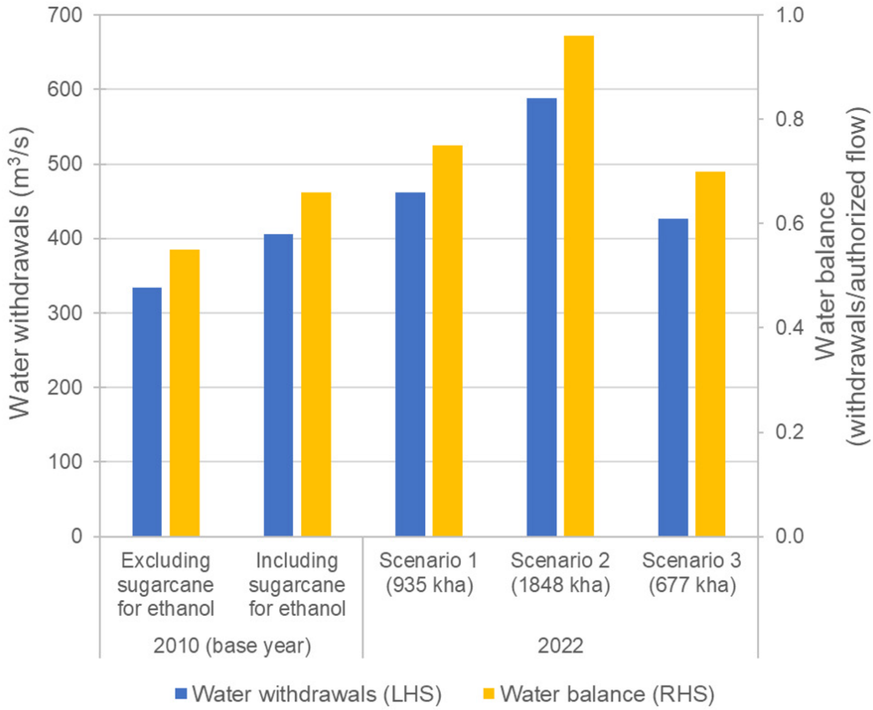

FIG. 3. Water withdrawals and water balance under alternative scenarios of sugarcane ethanol expansion, Paranaíba River Basin, Brazil. Note: kha — kilohectares.

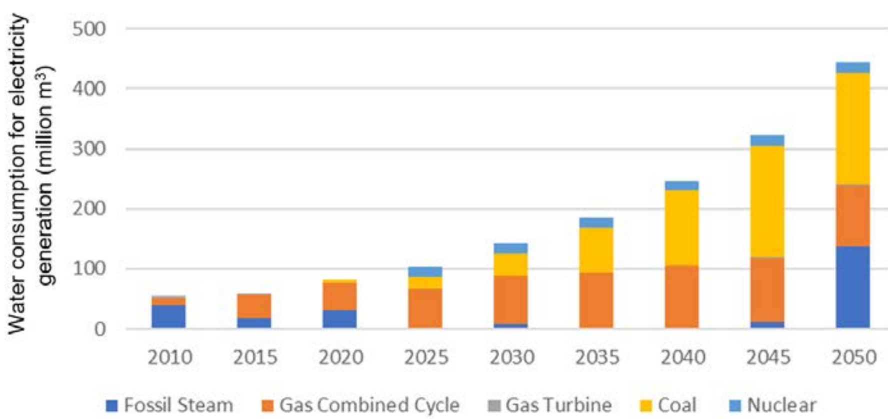

FIG. 4. Water consumption for power generation under reference scenario, Syrian Arab Republic. Fossil steam refers to steam cycle generation using fuel oil.

electricity generation by 2050 under a reference scenario from the Syrian Arab Republic study. Appropriate selection of electricity generation technologies and cooling systems can limit this water consumption (e.g. see Refs [26, 27] for nuclear power), although the Syrian Arab Republic study identifies important trade-offs between energy affordability, water demand and climate change mitigation. Despite these challenges, the integrated CLEW approach in the study helps to underline the fact that water consumption in electricity generation is far below municipal and agricultural water demands (which together still account for over 95% of projected water demand in 2050), and many efficient options to reduce overall water consumption also exist outside the energy sector.

The studies also considered how water–energy linkages are likely to be impacted by future changes to climate affecting precipitation and evapotranspiration. These effects can be both direct and indirect, and substantial in scale. For example, the Syrian Arab Republic study refers to a 20–30% decrease in precipitation anticipated in the Jordan River Basin by 2040 [28]. Direct effects include changes to water availability and requirements for thermal power plant cooling and hydroelectricity generation. Indirect effects include reduced water availability for energy production arising from climate induced changes to agricultural and municipal water consumption. Furthermore, biofuel crop water needs will also be affected. In the Brazil study, for example, future climate conditions are estimated to increase sugarcane evapotranspiration by more than 3%. Figure 5 illustrates the impact on water withdrawals for Mauritius, under alternative scenarios of climate change and biofuel production. More pessimistic climate change projections necessitate additional water withdrawals to support biofuel production (in this case, sugarcane ethanol). This issue is discussed more broadly in Section 3.3.3.

3.3.1.2. Energy for water

As mentioned above, energy–water linkages explored in the CRP also include energy used in the extraction, distribution and treatment of water and wastewater. The CRP reports from the three countries facing the greatest water stress — Mauritius, South Africa and the Syrian Arab Republic — paid particular attention to these issues, motivated by concerns regarding increasing water demands and the impact of climate change on water availability. These studies all identified a risk that future water demands may exceed conventional water supplies, potentially requiring the deployment of more energy intensive options, such as desalination.

The Syrian Arab Republic study examined this issue in much greater detail and considered several desalination technologies along with an ambitious plan to transport water from the Euphrates and Aleppo Basin to Damascus.

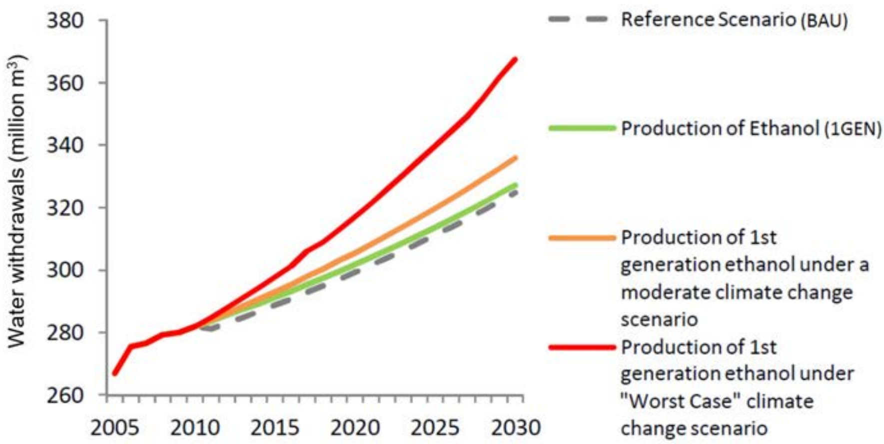

FIG. 5. Water withdrawals under alternative CLEW scenarios, Mauritius.

The analysis indicates that desalination can impose a burden on the electricity system, potentially increasing GHG emissions and electricity costs. In the Mauritius study, deployment of desalination is considered as a potential response to reduced rainfall due to climate change, in order to support the cultivation of sugarcane for biofuel production. However, under a pessimistic scenario of climate change presented in this study, the GHG emissions from the additional energy required for desalination and irrigation more than offset the emission reduction benefits from substituting the produced biofuel for petroleum fuels. In other words, the CLEW approach in these studies identifies a negative feedback loop between climate change, reduced water availability, desalination, energy use and GHG emissions. This again highlights the importance of integrated approaches to energy and water management, including in the selection of cooling and desalination technologies. Moreover, the Mauritius study highlights the sensitivity of a specific climate change mitigation option (biofuel from sugarcane) to climate change itself. The study suggests that switching to other biofuel crops, with lower water requirements and increased drought resistance, can reduce the need for energy intensive desalination. While this can improve the overall GHG balance, the lower biofuel yield from these crops increases costs and dependence on conventional fuels.

Unlike the national perspectives presented in the Mauritius and the Syrian Arab Republic studies, the South Africa study focused on water security and challenges in Cape Town, which is experiencing a rapid increase in population. The study explored many scenarios of water supply, demand and quality, along with options for water conservation, demand management and other interventions including additional groundwater extraction, water reuse and desalination. In addition to parameters of supply reliability, the study estimated energy requirements for these different scenarios and water management options. Figure 6 presents a snapshot of the scenario results indicating that scenarios with conservation and reuse are among the least energy intensive and can achieve relatively high water supply reliability (see blue markers in Fig. 6). While desalination can also significantly improve the reliability of the water supply, it is the most energy intensive measure (see the orange markers in Fig. 6).

Similar to the South Africa study, the analysis for the Syrian Arab Republic also examined options for water demand management and water reuse, to reduce or avoid the need to employ energy intensive water extraction options, such as desalination. This again illustrates an advantage of the integrated CLEW approach that can simultaneously assess strategies across different sectors.

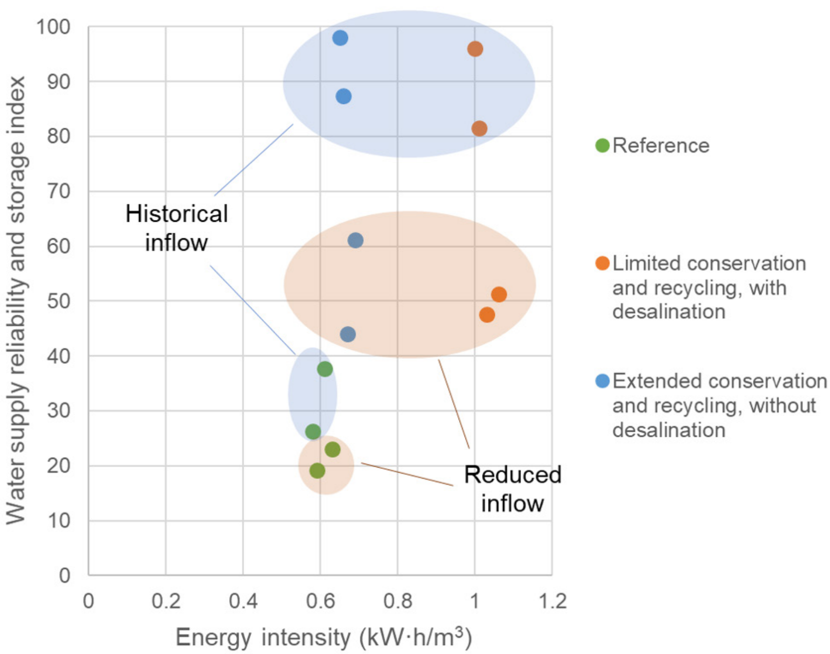

FIG. 6. Water supply energy intensity, reliability and system storage, Cape Town, 2030. The figure presents results for three combinations of water conservation measures and desalination ('Reference', 'Limited conservation…with desalination' and 'Extended conservation…without desalination') under two inflow scenarios indicated by the shaded areas ('Historical' and 'Reduced').

3.3.2. Energy–land linkages

3.3.2.1. Land for energy

As illustrated in Table 3, the representation of energy–land and land–water interactions was generally limited in the studies, with only three research teams applying a land use model (Lithuania, Mauritius, Thailand). Land use modelling in a CLEW assessment is particularly relevant for assessing potential biomass and biofuel crop yields and land suitability (including competition with other crops), which was a central policy focus of the Mauritius and Thailand studies. Other studies concerned with biomass (Brazil, Cuba) did not model land suitability or yields explicitly but instead applied stylized scenario assumptions. For example, the Brazil study presented three alternative scenarios of land used for sugarcane cultivation (see Fig. 3) but did not consider how these impacted other land uses. In this sense, the Brazil study is closer to a traditional assessment of water use, albeit for the cultivation of sugarcane for biofuel production, with system boundaries that do not include energy inputs, alternative land uses or the benefits of increased biofuel production.

The three studies modelling energy–land interactions sought to analyse biomass and biofuel expansion policies in the context of maintaining the production of food and industrial crops, non-energy use of biomass, protected areas and other land uses.[2] This approach allows for a consistent comparison of alternative bioenergy production options without the complication of other changes to land use or agricultural output. The Mauritius and Thailand studies also applied detailed geographic information system data on crop yields and suitability. This enabled the analysis to consider the optimal growing locations for biofuel crops accounting for climate, soil quality and other land uses (in addition to water and energy inputs).

The findings of the Mauritius and Thailand studies identify instances where crops with lower yields can be superior to crops with higher yields, due to higher tolerance to poor soils, low rainfall, pests, drought and/or flood. For instance, the Thailand study identified a large potential for cassava vis-à-vis more traditional sugarcane for biofuel production. This mirrors similar observations in Section 3.3.1.1 on water–energy linkages relating to biofuel crop selection, together illustrating the importance of regional variations in land suitability, water availability and relative crop performance. The integrated CLEW approach enables these to be considered together. Although not included in any of the CRP

[2] The Thailand study did not completely adhere to this approach and instead applied a range of different scenario assumptions for crops used for non-energy purposes (see Appendix II, Section II.8).

studies, the integrated analysis of land in the CLEW framework also provides for the broader analysis of (non-energy) agriculture, including options such as reducing agricultural output to preserve water supplies for municipal or energy needs, or increasing agricultural intensity to release land for other purposes.

Unlike Mauritius and Thailand, Lithuania has a relatively large amount of arable and forested land per capita (see Table 2). The Lithuania study identified the potential to significantly expand biomass (primarily wood) use in combined heat and power (CHP) applications, under policy targets aimed at increasing the share of renewable energy. Figure 7 shows that the country's relative abundance of arable land and forest resources means that this additional biomass demand can be met from existing forests and newly planted forests on unused land, without significant competition with agricultural or other needs.

3.3.2.2. Energy for land

In addition to the above 'land for energy' connections, energy–land linkages also include energy used in fertilizer production and in land preparation, cultivation and harvest (PCH). These are considered in the three studies applying land use modelling tools, which explored the impact of different fertilizer and land PCH requirements for different crops or different production methods for

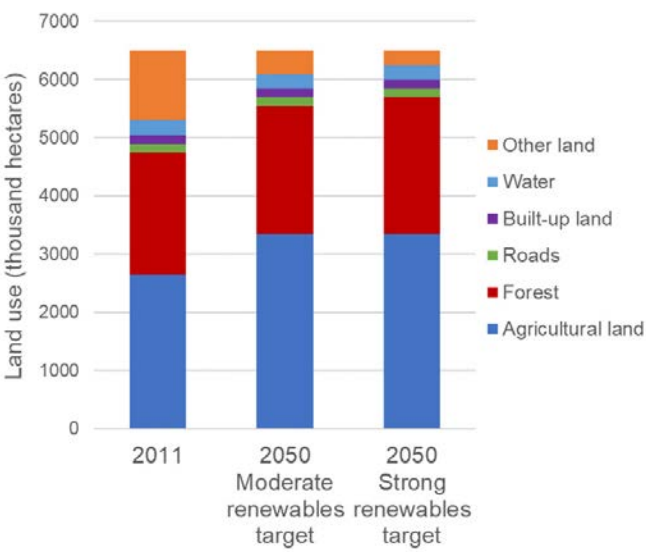

FIG. 7. Impact on land balance of expanded agriculture and forestry under alternative renewables targets, Lithuania.

the same crop. The associated energy inputs can vary significantly, as illustrated in the overall energy balance for biodiesel production shown in Fig. 8 for the Thailand study. This energy balance compares the energy content of the biofuel product with the energy inputs for fertilizer, land PCH, irrigation, biofuel synthesis and other activities for two different crop mixes. Together with the previously discussed variation in land and water requirements for biofuel crops, this further illustrates the complexity and the necessity for integrated approaches such as CLEW to support the effective management of multiple resources.

3.3.3. Land–water linkages

Most land–water interactions analysed in the studies relate to the use of water in agriculture (i.e. 'water for land'). While this also partly covers some of the 'land for water' impacts on water supply — particularly via evapotranspiration — other linkages, including the effect of land use and catchment management on the interception and infiltration of water, are not considered in the studies.

Concerning 'water for land', many of the linkages investigated in two of the studies applying a land use model (Mauritius, Thailand) have been discussed

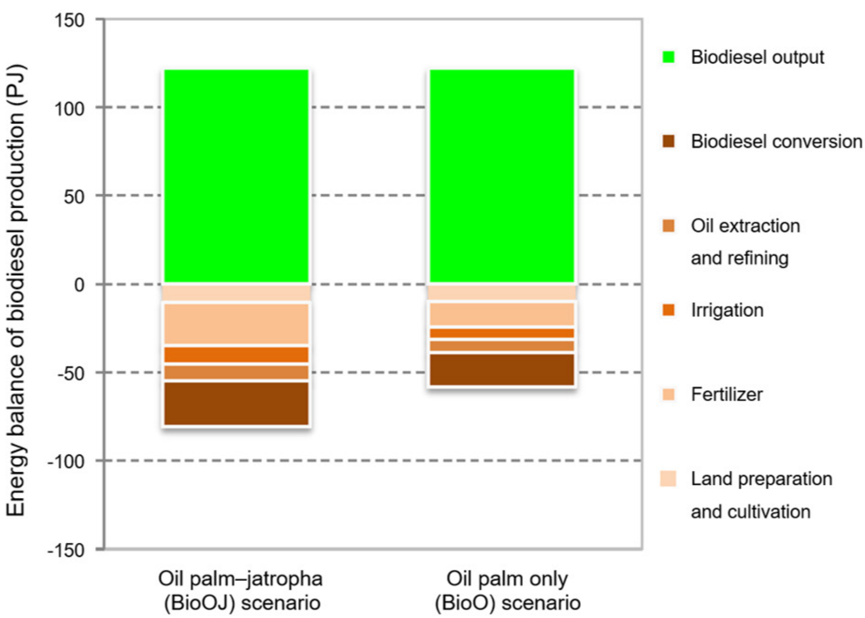

FIG. 8. Energy balance of biodiesel production from oil palm and jatropha (BioOJ) and oil palm only (BioO), Thailand, 2021.

above in the context of biomass and biofuel cultivation (‘water for energy’). Water use relating to biofuel production for the Brazil study has also been covered above. The third study applying a land use model (Lithuania) did not implement water use for agricultural purposes. Beyond the use of water in cultivation of biomass and biofuels, additional ‘water for land’ linkages include water used for food, fibre and fodder crops. As mentioned earlier, the Mauritius and Thailand studies investigated CLEW linkages under conditions in which the production of these other food and industrial crops was maintained, along with non-energy use of biomass, protected areas and other land uses. While this approach ensures consistency when considering only changes relating to bioenergy production, there exists the potential to further exploit the integrated CLEW method to examine alternative non-energy crop options.

3.3.4. Climate linkages

3.3.4.1. Climate and energy

As noted above for several studies, climate change can indirectly affect the energy sector via its impact on water availability: reduced water availability can affect the production of biomass and biofuels and increase energy needs in water supply. One of the CRP studies also analysed additional linkages between climate and energy by downscaling global climate change impacts under a scenario with a 2°C increase in temperature by 2050 to estimate local impacts in Cuba. The study considered the direct impact of higher temperatures on electricity demand for space cooling in buildings, which is estimated to be 10% higher by 2050 on account of climate change. The Cuba study also accounted for the impact of higher temperatures on the efficiency of thermal power plants, along with reduced biomass production yields. The combination of these impacts from climate change (i.e. increased energy demands, reduced generation efficiencies, lower biomass availability) on electricity generation is shown in Fig. 9. Electricity generation using fossil fuel increases, leading to a 15% increase in CO_2 emissions in 2050, compared with the situation without climate change.

3.3.4.2. Climate linkages with land and water

Climate impacts on water (such as changes in precipitation, transpiration and evaporation) are explored through a scenario approach in most of the studies considering this aspect (Brazil, Cuba, Mauritius, South Africa). This approach entails assessing the impact of climate change on the land–energy–water system by comparing scenarios with and without climate change, rather than by directly applying a climate model linked to land, energy and water models. As discussed

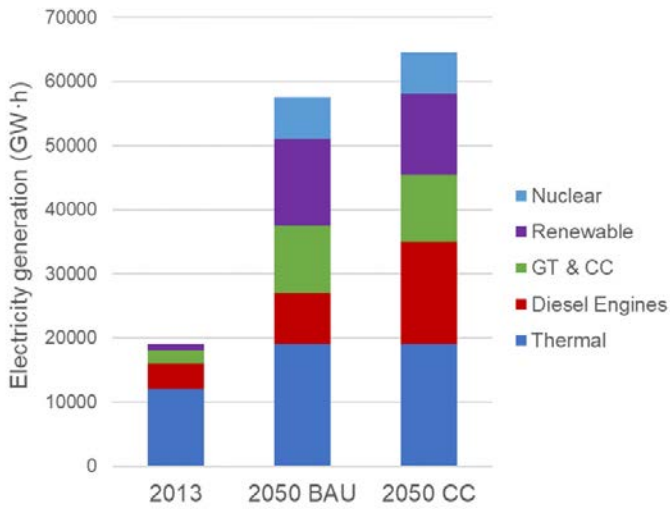

FIG. 9. Electricity generation in business as usual (BAU) and climate change (CC) scenarios, Cuba. Note: GT & CC — gas turbine and combined cycle.

in the context of energy–water linkages (see Sections 3.3.1 and 3.3.1.1), climate change impacts on water propagate via effects on hydroelectricity output, municipal water supply and agriculture, in turn increasing demand for irrigation and desalination, or leading to reduced biomass yields. To recap, the Brazil and Mauritius studies analysed linkages between climate change and water availability for biofuel production: the additional water stress from climate change in the Mauritius study was projected to result in increasing needs for desalination and irrigation or require a shift to alternative crops. The Cuba study assumed reduced biomass yields due to lower water availability (without modelling water), while the South Africa study considered scenarios for municipal water supply that included reduced inflows consistent with climate change, increasing the need for desalination or aggressive water conservation and reuse.

In comparison with climate–water linkages, the studies have a more limited representation of the positive and negative impacts of climate on land, including changes such as longer growing seasons, higher temperatures (affecting yields), CO_2 fertilization, increased pestilence and more extreme events (heat waves, storms). The Cuba study mentions the negative effect on potato yields due to temperature increase, but without a land use model it did not analyse how maintaining output (or switching to a more tolerant crop) would affect land, energy and water use more broadly.

Since the studies (and the CLEW approach generally, see Section 2.2) account for climate change through a scenario approach rather than by linking a climate model with land–energy–water models, the effect of changes to land and water use on climate are generally not represented. For small countries, such changes are likely to have a negligible impact on global climate. However, local land and water use changes may nevertheless affect the local and regional climate and weather, such as through changes to transpiration, evaporation and albedo. For larger countries (e.g. Brazil), the impact of changes to land, energy and water use can potentially have a significant impact on global climate (although it should be noted that the Brazil study was concerned with a much smaller subregion within the country). Accordingly, care is required in accounting for the climate dimension in CLEW studies of larger countries (or countries responsible for a substantial proportion of global emissions) and for CLEW studies exploring more significant land or water use changes that could affect local climate patterns.

3.4. INTEGRATED CLEW NEXUS SYNTHESIS

Table 4 summarizes the bilateral CLEW linkages across the studies discussed above. As mentioned, one important observation is that some axes of the CLEW nexus were not covered in detail in the CRP studies. These include several linkages related to land, including the impact of climate on land (other than impacts related to water), and the impact of land use changes on climate and weather via changes to transpiration, evaporation and albedo. The role of land in water availability (i.e. ‘land for water’) was also not considered beyond evapotranspiration, despite the potential for changes to land use to affect hydrology in other ways (e.g. interception, infiltration). However, the significance of some of these linkages may be limited and, given the scope of the individual CRP studies, it is reasonable that these connections received a lower priority. This may also apply to part of the climate–water axis that was not covered in the studies, specifically any effects from changes to water use on climate and weather. Nonetheless, these linkages may deserve further attention in some specific cases, such as for the analysis of substantial changes to land use.

Among the CLEW linkages covered in the studies, impacts of climate on water were identified as being significant in several countries. On the other hand, relatively few studies considered the direct effects of climate change on the energy sector, including impacts such as increasing energy demands (for cooling) and reduced generation efficiencies of thermal power plants. Multiple studies also analysed increasing bioenergy production to support policy goals related to energy independence and climate change mitigation. These studies noted the implications for water along with options to manage and reduce water stress by

TABLE 4. MATRIX OF CLEW LINKAGES IDENTIFIED AND ANALYSED IN THE CRP STUDIES

	Climate impact on	Land for	Energy for	Water for
Climate		n.a.	GHG emissions (Cuba, Lithuania, Mauritius, Syrian Arab Republic, Thailand)	n.a.
Land	n.a. (evapotranspiration covered in climate–water)		Fertilizer and PCH (Lithuania, Mauritius, Thailand)	Biomass/biofuels, alternative crops (evapotranspiration) (Brazil, Mauritius, Thailand)
Energy	Space cooling, power plant efficiency (Cuba, Mauritius)	Biomass/biofuels, alternative crops (Lithuania, Mauritius, Thailand, (Cuba))		Thermal power plant cooling, hydropower; bioenergy (via water–land) (Lithuania, Mauritius, Syrian Arab Republic, (Brazil, Thailand))
Water	Precipitation, evapotranspiration (Brazil, Mauritius, South Africa, Syrian Arab Republic, (Cuba))	n.a. (evapotranspiration covered via 'water for land' interactions)	Irrigation, desalination (Mauritius, South Africa, Syrian Arab Republic, Thailand)	

Note: GHG — greenhouse gas, n.a. — not applicable (not represented in the studies); PCH — preparation, cultivation and harvesting.

the careful selection of suitable locations and crops for bioenergy cultivation, and the potential need for additional irrigation and desalination. Some studies also analysed the potential role of desalination and irrigation to support agricultural and municipal water needs more broadly in the context of increasing demands and reduced water availability due to climate change.

In sum, two main themes emerged across several studies relating to: (i) bioenergy; and (ii) climate–water linkages. As noted, multiple studies in the CRP explored how biomass and biofuel production is linked directly to land, energy and water, and indirectly to climate. Given these linkages, the CLEW approach is essential for understanding the implications and interdependencies associated with policies aimed at promoting the production and use of bioenergy. In the case of water, Table 4 implicitly illustrates the cascade resulting from the impact of climate on the water cycle (precipitation, evapotranspiration). The impact on water availability directly affects the municipal water supply and indirectly affects 'water for land' (i.e. agriculture) and 'water for energy' (biofuel, hydroelectricity, cooling for power plants). Adapting to this change with efforts to maintain water availability and agricultural production affects the 'energy for water' axis (i.e. more energy may be needed for irrigation and desalination). These linkages are illustrated in Fig. 10.

As a final note, it is important to stress that these valuable insights only partially illustrate the potential of the CLEW framework, given that the objectives of some of the studies were not fully achieved owing to limited access to data, technical or financial resources. For example, the team for Mauritius noted issues relating to data availability including access to climate and geographic information system data with a resolution suitable for a small country such as theirs, as well as limited technical and financial resources to develop the necessary data to further improve their CLEW analysis. The report for the

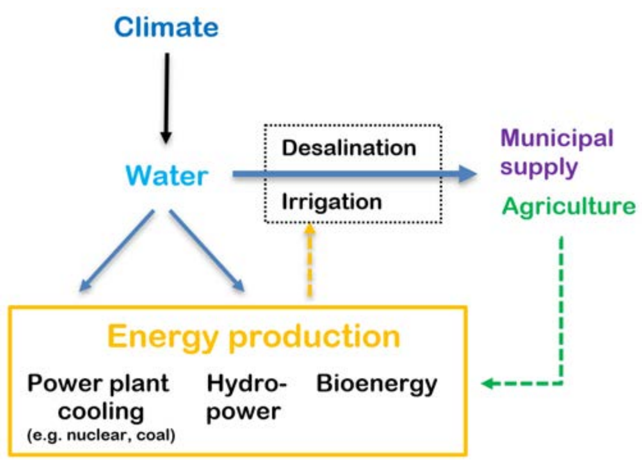

FIG. 10. Climate–water linkages have multiple effects on the energy system.

Cuba study also noted that it was not possible to implement water modelling or estimate the impact of climate change on renewable energy production owing to a lack of data. Options to address these challenges along with broader capacity building and policy insights are explored further in Section 4.

4. SUMMARY OF FINDINGS AND CONCLUSIONS

4.1. RESOURCE LINKAGES EVALUATED IN THE STUDIES

The CRP included analysis by ten research groups from countries facing diverse CLEW challenges. As discussed in Section 3, six of the country teams submitted final reports presenting CLEW analyses and it was possible to synthesize sufficient information from intermediate reports and other material to include another CLEW analysis (Mauritius) in this publication. One of the remaining countries submitted a final report presenting a more conceptual study on measuring progress towards sustainability (Germany).

The applications of the CLEW framework in the CRP cover diverse resource challenges and policy questions, ranging from a detailed analysis of water management options in an urban environment (i.e. Cape Town, South Africa) to long term national studies covering all resources (e.g. Mauritius). Accordingly, country research teams applied a range of assessment approaches and methodologies to analyse their domestic CLEW policy challenges. This diversity of methodologies and research questions means that resource interactions were not represented uniformly across the studies, as illustrated in Table 5. For example, only three teams applied a land use model and explicitly accounted for energy used for land and agriculture (e.g. fertilizer, harvesting). Energy used for water (irrigation, desalination) and water used directly for energy (power plant cooling, hydroelectricity) were also covered in fewer studies. Similarly, while several studies considered the impacts of climate change on land and water (e.g. crop yields, irrigation requirements), fewer accounted for climate impacts on energy (e.g. space cooling). Despite this, several insights emerged consistently from two fairly distinct groups of studies, related primarily to the value of the CLEW framework in the assessment of: (i) biofuels and biomass; and (ii) the impact of climate on water and energy.

TABLE 5. CLEW LINKAGES ANALYSED IN CRP STUDIES

	Policy focus	Land used for energy	Energy used for land	Energy used for water	Water used for energy	Water used for land	Climate impacts on energy	Climate impacts on water and land
Brazil	Biofuels				(L)	✓		✓
Cuba	Energy (biomass)	✓					✓	✓
Lithuania	Energy (biomass)	✓	✓		✓			
Mauritius	Biofuels	✓	✓	✓	✓	✓	✓	✓
South Africa	Water			✓				✓
Syrian Arab Republic	Energy–water			✓	✓			✓
Thailand	Biofuels	✓	✓	✓	(L)	✓		

Note: (L) — limited to water used for biofuel crops and represented via 'water used for land'.

4.2. KEY FINDINGS AND POLICY CONCLUSIONS

4.2.1. Biomass and biofuels

The studies demonstrate that the CLEW approach is essential for analysing the impact of biomass and biofuel production, and associated policies, given direct linkages to energy, water, land use and climate change. On the one hand, bioenergy expansion has the potential to improve energy security and reduce GHG emissions. On the other hand, the cultivation of biomass and biofuel crops requires substantial land, energy and water inputs, and can be affected by changes to climate. In addition, biomass and biofuels compete with food and other crops.

Several of the CRP studies that focused on biofuels (Brazil, Mauritius, Thailand) noted the potential negative effects of expansion plans on water resources, particularly given the impacts of climate change. The latter can also reduce the potential energy–climate benefits of biofuels if additional energy inputs are required for irrigation or desalination (Mauritius). Crop selection for biofuel feedstock can also influence multiple dimensions of the land–energy–water nexus and is thus an important consideration to avoid some of the negative effects. Crops with lower water and fertilizer requirements, such as jatropha, cassava, maize and miscanthus, may be attractive in some cases, but this needs to be balanced against overall productivity and land and energy requirements (Mauritius, Thailand). A related consideration is crop choice in different regions within a country, accounting for water and land availability, climate and productivity, along with potential genetic improvements to crops, changes to soil management and irrigation efficiency.

These issues are also pertinent for biomass used for electricity (which was significant in the Cuba and Lithuania studies), although the potential to source biomass from forests and waste streams (agriculture, food and paper industries, municipal sources) can mitigate some of the CLEW challenges.

4.2.2. Energy–water–climate

While climate change will continue to affect land, energy and water resources, a systemic impact on water availability due to changes in precipitation, evaporation and transpiration was identified across several studies. The studies illustrated how changes to water availability can propagate to the energy sector (e.g. hydroelectricity output) and agriculture (e.g. reduced crop yields), which in turn can lead to adaptation responses such as increased irrigation and desalination, further affecting the energy sector (Brazil, Cuba, Mauritius, South Africa). One other impact from climate change reflected in the studies was increased energy demands for space cooling (Cuba, Syrian Arab Republic).

In the energy sector, potential trade-offs were identified between water use, energy affordability and climate change mitigation (Mauritius, Syrian Arab Republic): in the case of thermal power plants, lower water and/or carbon intensity can only be achieved at higher costs. However, the CLEW approach also helps to compare sectoral resource uses, for instance highlighting that the amount of water used in power generation is far below municipal and agricultural demands. The implication is that water efficiency options outside the energy sector may be a more important policy target than efforts to adopt expensive options such as dry cooling to reduce water use in thermal power plants. Water efficiency outside the energy sector was the focus of one CRP study (Cape Town, South Africa) concerned with the vulnerability of municipal water systems to increasing water demands combined with reduced water inflows due to climate change. While desalination was one (energy intensive) option to address water challenges, some of the water–energy trade-offs could be avoided with other interventions (i.e. conservation, recycling) that may be more efficient to ensure a safe and secure water system in the future.

While for many studies the results are illustrative and preliminary in terms of specific policy recommendations, they nonetheless illustrate the potential benefits of the integrated CLEW framework compared with traditional single resource assessment approaches. Despite the limitations, the analysis demonstrates interdependencies between climate, land, energy and water, and provides proof of concept of the suitability of CLEW to evaluate these linkages to support policy development. Moreover, the CRP work advances the state of knowledge of CLEW, improves the knowledge base, tools and toolkits available for integrated assessment, and establishes a solid foundation for future applications and studies. Looking more broadly to the needs of IAEA Member States, the CRP illustrates that the CLEW approach can support countries to develop energy strategies that are consistent with broader aspects of sustainable development, enabling, for example, a more comprehensive assessment of the suitability of nuclear energy.

4.3. LESSONS, LIMITATIONS AND FUTURE DIRECTION

4.3.1. Potential further CLEW applications

Despite the useful insights from the CRP, the very broad scope of challenges in the CLEW domains means that there remain many areas of potential further study. For instance, it is likely that a different set of CLEW interdependencies, not directly covered in the CRP, exists in countries with a reliance on traditional biomass (via additional energy–land interactions) or in more extreme environments (sub-arctic/tundra, desert) where local resources are extremely limited and vulnerable. The latter may, however, represent a challenge for the CLEW framework since these regions often rely on external sources of energy, water and/or agricultural products potentially outside the geographical scope of a CLEW analysis — this was intimated in some of the CRP studies (e.g. in relation to imports and exports of energy in the Lithuania study). Depending on the nature of these cross-border exchanges, additional analysis or complementary approaches may be needed.[3] Another area for potential further study relates to the impact of changes to land use (and possibly water) on local and regional climate and weather patterns, which were not discussed in the CRP studies. This may be particularly relevant for major land use changes affecting the local microclimate.

There is also additional potential to apply the CLEW framework to different policy questions. While many of the CRP studies were concerned with policies targeting the energy sector (e.g. renewable targets, biofuel production), relatively few focused on policies targeting water and land resource management (the South Africa study being the main exception). This may represent an interesting area for further analysis given that there may be significant co-benefits to the energy sector arising from improved water management (affecting energy use in irrigation, pumping, treatment and desalination, and the operation of hydroelectric plants). There is also further scope to assess other technologies with strong interactions across the CLEW domains: for example, hydroelectricity interacts with water, agriculture and climate, but was not as well covered in the CRP studies as biomass and biofuels, which exhibit similar interactions.

4.3.2. Methodology challenges

The CRP studies have also helped to identify the requirements for a successful CLEW analysis, in terms of methodology and scenario definition. This includes achieving full coverage of the relevant CLEW domains, in terms of both models and data. The latter represents a significant challenge in some cases and requires investment in data collection and processing to avoid the exclusion of key resources as was the case in some studies in the CRP (e.g. water and climate in Cuba). Once implemented, such data and model development enables the possibility to conduct many scenario analyses, although this was not necessarily fully exploited in the studies (e.g. Lithuania). The other key requirement is to ensure policy relevant and logically consistent scenario definition across all relevant dimensions. In some of the CRP studies, additional insights would have been provided by analysis of additional scenarios (or slight modifications to scenario design), without requiring additional model development or data collection (e.g. Syrian Arab Republic, Thailand).

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[3] While such challenges can also exist in traditional single resource studies, the broad resource coverage in a CLEW study increases the chance of at least one resource system extending beyond the study region. This could be managed to some degree with scenario definition (e.g. assuming fixed inputs or outputs beyond the geographical boundary), but in cases with significant cross-boundary interactions, other approaches may be needed, such as broadening the geographical boundaries of the CLEW study.

Beyond these research related elements of a successful CLEW analysis, there are a number of other institutional and capacity requirements that are particularly relevant in developing countries seeking to implement a CLEW approach. These are discussed in Section 4.4.

4.4. BUILDING CAPACITY IN THE USE OF THE CLEW FRAMEWORK IN DEVELOPING COUNTRIES

Upper and lower middle income countries were represented in seven out of the ten studies in the CRP (see Table 2). Challenges relating to the CLEW nexus may be particularly acute in such countries given lower levels of access to energy, food and water, and greater vulnerability to climate change due to poverty, geography and infrastructure deficits. At the same time, these countries often have less developed policy and planning institutions compared with high income countries and may benefit substantially from support in establishing a CLEW approach to resource planning and management.

The CRP has identified several ways to support effective capacity building in the use of the CLEW framework in developing countries, which tend to reinforce insights from other IAEA capacity building activities. One key element for building capacity with CLEW is the use of open access tools. This reduces financial and technical barriers to establishing, building and maintaining national expertise, and enables different organizations to share and exchange tools. However, building capacity also requires support in training and know-how transfer from CLEW tool developers and other practitioners. This represents one area in which support from international organizations (e.g. IAEA, United Nations, multilateral and national aid agencies, non-governmental organizations) can be highly effective, for example in facilitating training or bringing together experts across countries for knowledge sharing among CLEW practitioners (with this CRP as one such example).

A further element for the successful use of the CLEW framework involves ensuring the engagement of relevant domestic governmental agencies (i.e. the agencies tasked with CLEW management and broader planning and development). Interagency cooperation across the CLEW domains can help with identifying relevant policy questions and sources of data and increase the likelihood that the integrated strategies from a CLEW analysis are adopted consistently across government departments. This cooperation across government agencies should ideally be facilitated through high level engagement (i.e. by senior management), which can also serve to ensure that key policy questions are identified and addressed in a CLEW analysis. International organizations may be able to contribute to securing this buy-in by senior management.

The importance of data has been mentioned throughout this publication and, in addition to domestic government agencies, key data sources include universities, the private sector (e.g. businesses, consultants) and international organizations (e.g. IAEA, United Nations, international research organizations, non-governmental organizations). Depending on domestic circumstances, identifying these sources and establishing relationships for data exchange are important first and ongoing steps for implementing a CLEW approach to resource management and planning.

Overall, the CLEW framework is well suited to supporting countries to build capacity in integrated planning for land, energy and water land resources, and can help to establish and maintain collaboration across government agencies and encourage a more integrated policy process. The IAEA and other United Nations partners can play a complementary role by providing technical assistance and developing the CLEW framework to support countries in their efforts to reach the United Nations SDGs. By integrating SDGs in energy planning, the CLEW framework augments the IAEA's well established suite of planning tools used by countries to develop strategies to meet growing energy demands while improving energy security, reducing environmental and health impacts, and mitigating climate change.

Appendix I

DEVELOPMENT OF THE CLEW FRAMEWORK AND THE ROLE OF THE IAEA

The idea to respond to the need for an integrated assessment framework covering critical resources for sustainable development was developed in 2009–2010 between the IAEA, the International Institute for Applied Systems Analysis (IIASA), the Stockholm Environment Institute (SEI), the United Nations Industrial Development Organization (UNIDO), and, soon after, the KTH Royal Institute of Technology (see Ref. [16]). The CLEW framework emerged from this collaboration.

The CLEW framework was tested with a first case study in Mauritius in 2011 analysing cross-sectoral impacts of biofuel policies [13]. The framework was then presented to the international community at the Rio+20 Conference on Sustainable Development in 2012, generating significant interest. Around the same time, the IAEA established a CRP on CLEW with ten participating countries — Australia, Brazil, Cuba, Germany, India, Lithuania, Mauritius, South Africa, the Syrian Arab Republic and Thailand.

In 2014, the CLEW framework was the subject of a special thematic chapter in the Prototype Global Sustainable Development Report [29], entitled "The climate–land–energy–water–development nexus". Successful demonstration of CLEW applications led to further international interest from 2015, particularly given the relevance of the framework to the Agenda 2030 SDGs [11]. Following the presentation of the CLEW framework by the IAEA and its academic partners to the United Nations Department of Economic and Social Affairs (UNDESA) and the United Nations Economic Commission for Europe, UNDESA included the CLEW framework in the suite of tools it offers in capacity building activities to support sustainable development policy and the SDGs. The following year, the CLEW framework was presented at the launch of the UNDESA capacity building programme on Modelling Tools for Sustainable Development Policies and its associated web platform.[4] Around the same time, the KTH Royal Institute of Technology established a postgraduate research programme on CLEW.

In 2016 and 2017, the IAEA supported the development and delivery of training material on CLEW (lectures, exercises, data visualization), established a formal collaboration on CLEW with the United Nations Development Programme (UNDP) and, with UNDESA and UNIDO, showcased the CLEW framework at the 23rd Conference of the Parties (COP23) to the United Nations

[4] See https://un-modelling.github.io

Framework Convention on Climate Change. These ongoing development and dissemination activities have generated increasing interest among governments and other organizations to apply the CLEW concept as part of their assessment practices. Starting in 2016, several countries have initiated national capacity building projects on CLEW with the support of the IAEA, UNDESA and UNDP.

Appendix II

SUMMARIES OF CRP COUNTRY PROJECTS

Research teams from ten countries participated in the CRP on Assessing Interdependencies between Energy, Water, Land Use and Climate Change. The project included Australia, Brazil, Cuba, Germany, India, Lithuania, Mauritius, South Africa, the Syrian Arab Republic and Thailand. These countries vary in terms of size, geography and climate, economic development, land, energy and water endowments, and their contribution to climate change (see Table 6). Based on 2014 data the countries fall into lower middle, upper middle and high income groups, range from small to large in terms of population (from 1.3 million to 1.3 billion), with access to modern energy varying from limited to universal, and with per capita CO_2 emissions in the range of under 2 tonnes to 15 tonnes. Climate types range from arid and desert climates with around 250 mm precipitation per year to tropical climates with over 2000 mm per year. While Table 6 provides a broad comparative overview of the conditions (and potential challenges) facing each of the countries, it should be noted that the indicator values present only the average situation in each country, and regions within the countries may face very different conditions. This is illustrated in two of the country projects (Brazil, South Africa), which focused on a specific subregion within each country, with distinct characteristics. This diversity of conditions is ideal for testing the suitability of the CLEW framework discussed in this publication.

The national research teams applied a range of methodologies to analyse the CLEW challenges in each of their countries, including bottom-up partial equilibrium models and accounting frameworks, through to applications of institutional economics and political economy. Summaries for all the projects are presented in the following sections (excluding Australia and India, for which final reports were not submitted).

TABLE 6. INDICATORS FOR COUNTRIES PARTICIPATING IN THE CRP, 2014

	Australia	Brazil	Cuba	Germany	India	Lithuania	Mauritius	South Africa	Syrian Arab Republic	Thailand
Population (million)	23.5	204.2	11.4	81.0	1 293.9	2.9	1.3	54.1	19.2	68.4
Rural population (%)	11	15	23	25	68	33	60	36	43	51
GDP (current US $/capita)	62 215	12 027	7 051	47 903	1 573	16 555	10 154	6 480	—	5 942
GDP (current PPP $/capita)	46 446	16 192	—	47 058	5 678	28 179	19 231	13 127	—	15 647
Income level	High	Upper middle	Upper middle	High	Lower middle	High	Upper middle	Upper middle	Lower middle	Upper middle
Main climate types	Tropical Subtropical Arid Temperate	Tropical	Temperate	Tropical Subtropical Arid Mountain	Temperate	Tropical	Subtropical Temperate	Arid/desert Mediterranean	Tropic	
CO_2 emissions (t/capita)	15.4	2.6	3.0	8.9	1.7	4.4	3.4	9.0	1.6	4.6
Land area (thousand km^2)	7 682	8 358	104	349	2 973	63	2.0	1 213	184	511

TABLE 6. INDICATORS FOR COUNTRIES PARTICIPATING IN THE CRP, 2014 (cont.)

	Australia	Brazil	Cuba	Germany	India	Lithuania	Mauritius	South Africa	Syrian Arab Republic	Thailand
Agricultural land area (thousand km^2)	4 063	2 826	63	167	1 796	30	0.9	968	139	221
Arable land (ha/capita)	2.00	0.39	0.27	0.15	0.12	0.80	0.06	0.23	0.24	0.25
Electricity consumption (kW·h/capita)	10 078	2 601	1 434	7 035	806	3 821	2 183	4 229	950	2 540
Access to clean energy for cooking (% of population)	100	93	87	100	34	100	99	82	100	76
Average precipitation (mm)	534	1 761	1 335	700	1 083	656	2 041	495	252	1 622
Annual freshwater withdrawals (% of resources)	4	1	18	31	53	4	26	35	235	26

Source: See http://data.worldbank.org/data-catalog/world-development-indicators

Note: Shading indicates high (green), moderate (yellow) or low (red) land, energy and water resource access and availability or, in the case of CO_2 emissions per capita, low (green), moderate (yellow) or high (red) emissions; GDP — gross domestic product; PPP — purchasing power parity.

II.1. SUMMARY: BRAZIL — PARANAÍBA HYDROGRAPHIC BASIN

II.1.1. Introduction

This summary is based on the final CRP report Impacts of Biofuels Production on Water Resources: Case Study of Ethanol Production from Sugarcane in the Paranaíba Hydrographic Basin[5] (see also Ref. [30]).

II.1.2. Situation assessment

Brazil has long been a leader in biofuel production. However, increasing demands have led to production moving into new areas, raising concerns about the potential for detrimental impacts on food and water security. Changing climate conditions are also expected to affect water availability and requirements, creating an additional threat to water security. These factors are playing out in the Paranaíba River Basin in the Central West and Southeast Regions of Brazil, where there have been significant changes in land and water use due to expanding ethanol production.

II.1.3. Methodology and scenarios

This study analyses the potential impact on water and land resources under alternative future scenarios of sugarcane cultivation (for biofuel) in the Paranaíba River Basin, accounting for the impact of climate change. Key inputs to this analysis include the water footprint of sugarcane ethanol (i.e. the volume of water used in the agricultural stage of production), which comprises so called ‘green’, ‘blue’ and ‘grey’ water flows. Green water flows refer to precipitation that evaporates from the land surface, primarily from agriculture, and that does not run off or recharge groundwater. Blue water flows refer to water runoff into a river basin that is utilized and not returned to the river basin. Grey water flows refer to water returned with associated process pollutants.

CROPWAT 8.0 [21] was used to estimate green (i.e. precipitation) and blue (i.e. irrigation) water requirements for sugarcane production in the basin based on climatic conditions taken from the CLIMWAT 2.0 [22] and New LocClim databases. For comparative purposes, the same crop water footprint was calculated for sugarcane produced in the state of São Paulo, which is the largest sugarcane producer in Brazil.

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[5] By N.P. Fachinelli and A.O. Pereira, Jr., Energy Planning Program, COPPE (Alberto Luiz Coimbra Institute for Graduate Studies and Research in Engineering), Federal University of Rio de Janeiro, Brazil.

Three sugarcane expansion scenarios were analysed in the study: two of which were taken from the Brazilian Ministry of Agriculture, Livestock and Food Supply [31]; and the third from a study conducted by the United States Department of Agriculture [32]. These scenarios consider widely different sugarcane expansion plans in the Paranaíba River Basin (see Fig. 3).

In addition to the sugarcane expansion scenarios, future sugarcane water requirements (in m^3/t) for the Paranaíba River Basin were estimated for different climatic conditions under the IPCC A2 and B2 climate scenarios [33, 34]. For the climate change scenarios, the total evapotranspiration and water requirements for the base and climate scenarios are shown in Table 7. For comparison, water withdrawals (i.e. blue water) from the basin for sugarcane destined for ethanol production in 2010 were around 2.3 billion m^3.

II.1.4. Selected findings and conclusions

The water balance for the Paranaíba River Basin already exhibited some degree of impairment in 2010, in terms of both withdrawal and consumption demands. When the withdrawal demand is considered, the basin was already in a state of alert (i.e. more than 50% of authorized flows were being withdrawn). By 2022, the three sugarcane expansion scenarios lead to further impairment of the basin's water resources (see Table 8). In the scenario with the largest expansion of sugarcane cultivation, the water balance becomes highly critical (with close to 100% of the authorized flows being withdrawn). On the other hand, this scenario

TABLE 7. SCENARIO ASSUMPTIONS FOR IRRIGATED ETHANOL SUGARCANE, PARANAÍBA RIVER BASIN

Climate conditions	Evapotranspiration (mm/year)	Water flow (m^3/t of sugarcane)*			
		Green	Blue	Grey	Total
Base (1961–1990)	1877	169	75	7	251
A2 climate (2010–2040)	1941	179	73	7	259
B2 climate (2010–2040)	1941	178	74	7	259

* For comparison, the São Paulo region has lower water requirements (with base climate conditions of: green = 150 m^3/t; blue = 45 m^3/t; and grey = 7 m^3/t).

TABLE 8. WATER AVAILABILITY, WITHDRAWAL DEMAND AND BALANCE, PARANAÍBA RIVER BASIN, 2022

Scenario	Surface water availability (m^3)		Total withdrawal demand (m^3/s)	Water balance	
	Reference flow Q95%	Authorized flow		(Withdrawal demand/ reference flow)	(Withdrawal demand/ authorized flow)
2010	1225.64	612.82	406	0.33	0.66
Scenario 1	1225.64	612.82	462	0.38	0.75
Scenario 2	1225.64	612.82	588	0.48	0.96
Scenario 3	1225.64	612.82	427	0.35	0.70

produces around 80 million tonnes of additional sugarcane compared with the amount produced in 2010 (in the order of 10% of total production in Brazil), which could be fully converted to around 140 petajoules of ethanol, potentially reducing CO_2 emissions by around 10 million tonnes (assuming this ethanol replaces gasoline).

This analysis indicates that continued rapid expansion of sugarcane cultivation for ethanol production will potentially have large negative impacts on water resources in the Paranaíba River Basin. However, this needs to be balanced against the need to mitigate climate change and pursue other aspects of energy sustainability, requiring further integrated analysis of energy, water, land use and climate change to identify a sustainable growth path for biofuel production in Brazil. The study also shows that while indicators of the volume of water consumed are useful for the analysis of potential impacts on basin level water resources, they do not account for other inputs that can change productivity such as soil management or genetic improvements to crops. Furthermore, indicators of grey water requirements did not account sufficiently for toxicity issues, biodegradability or effluent treatment.

The results presented in this case study demonstrate the importance of assessing the condition of resources affected by the expansion of sugarcane cultivation in regions of water deficit and water use conflicts, such as the Central West Region in Brazil. This can help to compare the sustainability of different options for expanding biofuel production and to aid the selection of appropriate basins and zones for ethanol expansion that minimize impairments to water resources. Such an integrated approach can provide input to decision makers at the federal and state level, as well as for state banks seeking to support the expansion of biofuel production.

II.2. SUMMARY: CUBA

II.2.1. Introduction

This summary is based on the final CRP report Case Studies to Analyze Climate, Land, Energy, Water (CLEW) Interactions in Cuba.[6]

II.2.2. Situation assessment

As a developing island State, Cuba is vulnerable to the impacts of climate change, and thus adaptation and mitigation represent policy priorities. At the same time, Cuba is dependent on imports of food and energy. To address some of these issues, Cuba has plans to increase the utilization of renewables and to reduce dependence on imported fuels for power generation to produce a cleaner, more diverse and more efficient energy supply [35]. Linkages between climate change, energy and water affect energy planning options: climate change has the potential to increase energy demands (for space cooling), reduce power generation efficiency and affect yields and water requirements (and supply) for renewable biomass production.

II.2.3. Methodology and scenarios

Two scenarios to 2050 were developed and analysed in this study to identify the nature and magnitude of linkages between climate change and energy. The first is a business as usual (BAU) scenario built around future population and gross domestic product (GDP) projections (see Table 9) that incorporates planned policies in the energy sector, including policies seeking to increase the utilization of renewables and reduce dependence on imported fuels for power generation, as well as to decrease costs and environmental impacts [35]. The second climate change scenario assumes the same demographic, economic and policy developments, but also accounts for the impacts of climate change that increase electricity demand (e.g. space cooling in buildings), while reducing power generation efficiency and biomass production yields (e.g. bagasse production assumed to grow at 2% per year versus 5% per year in BAU).

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[6] By CUBAENERGIA, Cuba.

TABLE 9. SCENARIO ASSUMPTIONS FOR POPULATION AND GDP, CUBA

	2012	2015	2020	2025	2030	2035	2040	2045	2050
Population (million)	11.16	11.2	11.12	11.03	10.91	10.75	10.6	10.58	10.56
Growth rate (%)		0.1	−0.1	−0.2	−0.2	−0.3	−0.3	0.0	0.0
GDP (US $ billion)	50.3	55.1	64.2	74.8	87.1	101.4	118.2	137.6	160.3
Growth rate (%)		3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1

This study used climate change projections based on representative concentration pathway scenarios in the IPCC report Climate Change 2013: The Physical Science Basis [36], with global mean surface temperatures increasing by between 1.0 and 2.0°C by 2046–2065. The Providing Regional Climates for Impacts Studies (PRECIS) model was used to estimate temperature impacts in the Caribbean region by 2050 for a case in which surface temperature increases by 2.0°C. The CROPWAT model [22] was applied to estimate possible irrigation water requirements for sugarcane production in Santis Spiritus Province with and without climate change in 2012. However, integrated water modelling for future periods was ultimately not possible in this study due primarily to a lack of data. Overall final energy demand was modelled in MAED, while optimal mixes of fuels and electric generation mixes were quantified with MESSAGE.

II.2.4. Selected findings and conclusions

Compared with the BAU scenario, the climate change scenario includes additional requirements for electricity for space cooling in buildings. While it is also likely that there may be additional energy demands for irrigation and water pumping, this was not modelled owing to a lack of data.

On the supply side, the increased surface temperatures in the climate change scenario reduce biomass production and thus the availability of biomass for power generation. Compared with the BAU scenario, this results in an increase in fossil fuel energy generation (see Fig. 11), with CO_2 emissions about 15% higher in 2050 compared with the BAU scenario. Non-biomass renewables are not attractive owing to assumed high investment costs. It should also be noted that the impact of climate change on non-biomass renewables was not considered.

For water resources, the study considered many of the possible interactions between climate change and energy with water but did not model water

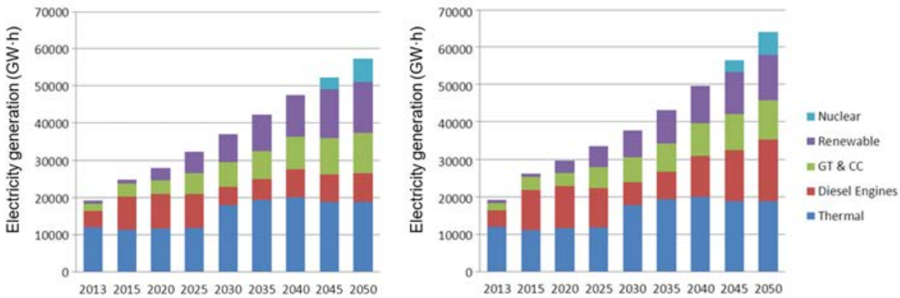

FIG. 11. Electricity generation in business-as-usual (left) and climate change (right) scenarios, Cuba.

consumption. Furthermore, other likely impacts of climate change were not modelled owing to a lack of data. As such, this study should be viewed as a useful first step in modelling these issues in Cuba, identifying several avenues for further integrated analysis.

II.3. SUMMARY: GERMANY

II.3.1. Introduction

This summary is based on the final CRP report Integrated Assessment of Climate Impact, Energy and Water Use in Germany against the Background of the UN Green Economy Model and Germany's Sustainability Strategy.[7]

II.3.2. Situation assessment

The German Sustainability Strategy [37] and the green economy concept of the United Nations adopted by the Government of Germany [38] lay out the pathway and goals towards a socioeconomic transition to a green society. Measuring progress towards these goals, and identifying areas requiring additional action, requires appropriate indicators of sustainable development: if current systems of sustainability indicators do not clearly signal that society is on an unsustainable path, the policy errors will be made and perpetuated [39].

[7] By H. Schlör, J.-Fr. Hake, Forschungszentrum Jülich, Institute of Energy and Climate Research, IEK-STE, Germany.

The study does not seek to present an integrated CLEW assessment, but rather a methodological contribution to the measurement of sustainability.

II.3.3. Methodology and scenarios

The study develops a sustainability gap index (SGI) measuring progress towards sustainability in Germany. The SGI provides information about the current status of sustainability to inform the public about the progress towards a green economy. The SGI is based on 37 indicators from the German Sustainability Strategy, and 2 additional indicators relating to water (which was not covered by other indicators in the Strategy). Of these 39 indicators, 18 relate to CLEW. The indicators are given an equal weighting when calculating the SGI for each of the four themes (intergenerational equity, quality of life, social cohesion, international responsibility) and a combined overall SGI.

II.3.4. Selected findings and conclusions

The analysis calculates the shortfall between the current status and the sustainability goals of Germany across the four themes. Progress towards the goals is not uniform. The analysis reveals that within each theme progress relating to CLEW systems lags behind overall progress. For example, within the theme of intergenerational equity, more progress has been made on indicators such as investment, education, innovation and public finances compared with indicators such as energy consumption, GHG emissions abatement, water quality and biodiversity, among others.

By providing information on progress towards the goals of the German Sustainability Strategy, the SGI can be used by policy makers to identify areas requiring additional action. While this analysis highlights some of the interdependences between individual CLEW systems and the quantitative goals in the German Sustainability Strategy, it does not provide direct insights related to linkages, trade-offs and synergies between climate, land, energy and water. Accordingly, as mentioned above, this study is not intended to present an integrated CLEW assessment but elaborates a complementary approach to measuring sustainability.

II.4. SUMMARY: LITHUANIA

II.4.1. Introduction

This summary is based on the final CRP report Assessment of Perspectives for Broader Use of Renewable Energy Sources in Lithuania Taking into Account Interdependencies among Energy Water and Climate Change.[8]

II.4.2. Situation assessment

The phasing out of nuclear power in Lithuania has created several challenges for the energy system by substantially increasing dependence on imported energy, energy prices and the share of fossil fuels in the energy supply. To address these challenges, a range of low carbon generation options are under consideration, including intermittent sources (e.g. solar, wind) and biomass. Biomass in particular represents a promising resource, but competition for land and water resources with agriculture is potentially significant. This analysis explores the impact of increasing the share of renewable energy in the Lithuanian energy system on climate change mitigation goals, and land and water use.

II.4.3. Methodology and scenarios

MESSAGE was used to simulate the energy system and linkages with land use in Lithuania. The optimization model covers all 60 municipalities and includes a comprehensive representation of energy resources and commodities, and technology options for energy extraction, transformation, transport, distribution and consumption. In addition, data on land use and agricultural productivity for the different municipalities and crops were incorporated in the model. Forestry information was also included to enable the assessment of the quantity of wood and wood waste that can be used for energy purposes, with a significantly different representation compared with agricultural crops due to differences in timescales for growing trees relative to crops. In addition to land, both agriculture and forestry require fertilizer and energy inputs, which are represented in MESSAGE. Water, on the other hand, was assumed to be sufficiently abundant owing to the favourable climate and the very limited use of irrigation in Lithuania. Nonetheless, water consumption for energy production was included in the model, which can account for the variation in potential water demand for irrigation and differences in seasonal and annual precipitation.

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[8] By A. Galinis, V. Lekavičius, D. Tarvydas, E. Norvaiša, E. Neniškis, I. Alėbaitė, Lithuanian Energy Institute, Lithuania.

Other production costs, such as labour, equipment and other inputs, were also represented.

The model was used to assess options for achieving an increasing share of renewable sources in Lithuania's final energy mix, taking into account sustainable development criteria, between 2010 and 2065. For this analysis, two scenarios were developed to demonstrate the functionality of the model: scenario A with a moderate renewable energy target (23% in 2020, 27% in 2030 and 30% in 2050); and scenario B with a more ambitious target (23% in 2020, 30% in 2030 and 55% in 2050).

II.4.4. Selected findings and conclusions

In both scenarios, increasing amounts of renewable electricity generation are deployed over time. Wind generation is the largest source of domestic electricity production, with increasing amounts of solar generation in later modelling periods (see Fig. 12). Biomass fired CHP is also a significant contributor, accounting for the second largest share of electricity generation for much of the time horizon. In scenario A, however, generation from biomass fired CHP declines over time (since existing incentives for biomass CHP are assumed to be phased out), while it increases in scenario B, with the higher goal for renewables more than offsetting the impact of the reduction in incentives. In both scenarios, electricity imports also play a large role, primarily owing to comparatively low electricity import price assumptions. In scenario A, import dependence remains relatively high to 2050, with domestically generated electricity comprising only 48% of total consumption in 2020 and 55% in 2050. In scenario B, the domestic share grows significantly to 84% in 2040, and Lithuania becomes a net electricity exporter by 2050. Gas fired generation and electricity imports are used to help balance intermittent wind and solar generation.

Land use is very similar under the two scenarios. In both scenarios, increasing amounts of agricultural land are used to meet the growing demand for agricultural products (domestically and for export). The share of 'other land' (mainly unused land) decreases while the share of agricultural land increases over time. Increasing demands for biomass are met with wood from existing forests (in scenario A) and from both existing forests and additionally planted forests (in scenario B).

While these results are primarily illustrative and preliminary in terms of specific policy recommendations, this analysis further demonstrates interdependencies between climate, land, energy and water, and provides proof of concept of the suitability of CLEW to evaluate these linkages to support policy development. These interdependencies have traditionally been analysed using

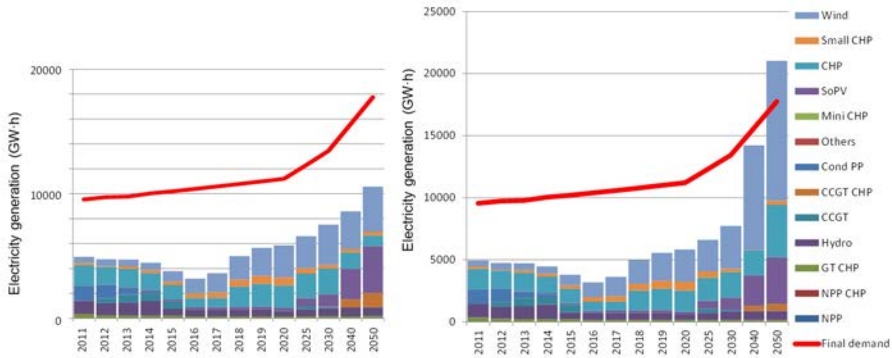

FIG. 12. Electricity generation by technology, scenario A (left) and scenario B (right), Lithuania. Note: CCGT — combined cycle gas turbine; CHP — combined heat and power; Cond PP — condensing power plant; GT — gas turbine; NPP — nuclear power plant; SoPV — solar photovoltaics.

different specialized models, and this study demonstrates that many of the issues can be analysed simultaneously within a single model.

II.5. SUMMARY: MAURITIUS

II.5.1. Introduction

This summary is based on Ref. [13] and the CRP progress report Mauritius — CLEW Case Study: Assessing Interdependencies among Energy, Water, Land-Use and Climate Change in Mauritius.[9]

II.5.2. Situation assessment

With limited land and energy resources, along with geographic isolation, Mauritius faces significant challenges relating to energy, water and land use, as well as being vulnerable to climate change. The country relies on imports for 70% of its food needs and over 80% of its energy needs, while the economy is highly dependent on exports of sugarcane [40]. To respond to climate change, while reducing dependence on energy imports, one option for Mauritius is to utilize sugarcane for ethanol production. This analysis seeks to examine the

[9] Report authored by I. Ramma, Agricultural Research and Extension Institute (FAREI), Mauritius.

potential implications of such a strategy on GHG emissions, land use, and water and energy balances.

II.5.3. Methodology and scenarios

The analysis utilized three models to analyse a set of scenarios covering 2010 to 2030: LEAP for energy, WEAP for water and the AEZ model for land use. The models were calibrated with common scenario assumptions for GDP growth, international energy and other commodity costs, domestic water constraints and other drivers. Interlinkages between energy, water, land use and climate change were also established.

Two climate change scenarios were defined: (i) a base scenario without climate change; and (ii) a scenario incorporating a reduction in precipitation due to climate change. Furthermore, three policy scenarios were 'nested' under each of the climate scenarios. The full set comprised:

(a) No climate change scenarios:
- — A BAU scenario where sugarcane continues to be grown for sugar production and the bagasse is used for electricity production;
- — A first generation ethanol (1Gen) scenario where sugar production is used to produce first generation ethanol with the bagasse used for electricity production;
- — A second generation ethanol (2Gen) scenario where both the sugarcane and bagasse are used to produce ethanol.

(b) Climate change scenarios:
- — A BAU scenario where sugarcane cultivation for sugar production and bagasse for electricity production continues, and with additional measures to meet crop water requirements under reduced precipitation;
- — A first generation ethanol scenario where sugar production is used to produce first generation ethanol with the bagasse used for electricity production, with additional measures in place to meet crop water requirements under reduced precipitation;
- — An alternative crop scenario where alternative drought resistant crops were considered for ethanol production.

II.5.4. Selected findings and conclusions

Among the no climate change scenarios, the BAU case shows a steady increase in water and energy requirements, along with GHG emissions, over the modelling period, driven mainly by economic growth and municipal needs (given that sugarcane production is unchanged in this scenario). In comparison, a switch to first generation ethanol (as in the 1Gen scenario) reduces gasoline imports and GHG emissions and provides an additional source of income for sugarcane producers. The switch also slightly increases water demand and electricity consumption for water pumping (see Fig. 5). A switch to second generation ethanol (in the 2Gen scenario) further reduces gasoline imports and GHG emissions in transport. However, the diversion of bagasse from electricity generation to ethanol production results in increased distillate and coal imports (for electricity generation), partially offsetting the reduction in GHG emissions in the transport sector. Furthermore, the cost of producing second generation ethanol offsets some of the savings from reduced gasoline imports.

In the climate change scenarios, the agricultural sector is significantly affected since the north and west regions of Mauritius become less suitable for rainfed sugarcane production, which significantly increases the demand for irrigation (see Fig. 5, which also includes a more extreme climate change scenario). Climate change is also expected to reduce hydroelectric generation and at the same time increase power demand for seawater desalination and water pumping. This reduced water availability makes sugarcane cultivation, and a switch to first generation ethanol, less attractive under these circumstances compared with the no climate change scenarios. Accordingly, switching to other crops requiring less water, such as jatropha, cassava, maize and miscanthus, may be more economically beneficial, while still helping to reduce GHG emissions from power production. However, these alternative crops would produce less ethanol at a higher cost than sugarcane.

These findings once again illustrate the benefits of the integrated CLEW approach, which in this case shows how the impact of climate change, particularly on water availability, can have a substantial bearing on the suitability of biofuel production and use for climate change mitigation. For instance, switching to ethanol production is attractive across several dimensions (energy, climate, reduced import dependence) in the absence of climate change, but is less robust once the effects of climate change are considered. Linkages between energy and water (hydropower, desalination, pumping, irrigation) are highlighted in this study.

II.6. SUMMARY: SOUTH AFRICA — CAPE TOWN

II.6.1. Introduction

This summary is based on the final CRP report Climate, Land, Energy and Water Strategies in the City of Cape Town (see also Ref. [41]).[10]

II.6.2. Situation assessment

Owing to population growth, it is estimated that water demand in Cape Town may outstrip supply by 2020. This is expected to be exacerbated by declining water inflows from reduced precipitation and increased evaporation due to climate change. This study analyses future options for water supply and demand in Cape Town and tracks the energy–water interaction arising from changing needs for water treatment and pumping, along with possible future desalination demands. The study also includes a shorter scoping analysis on the impact on irrigation of relocating horticultural activity within Cape Town.

II.6.3. Methodology and scenarios

The analysis utilized WESAT, which is based on the Stockholm Environmental Institute's WEAP and LEAP models. Since there are also some agricultural areas within the municipal borders of Cape Town, the Water Research Commission's SAPWAT3 model was used to model crop water demand for these areas.

Overall, residential demand for water accounts for 60% of delivered water, followed by commerce (15%) and industry (18%). Overall bulk water losses of 8% and reticulation losses of 21% are applied in the model. Future water demand projections are based on a Department of Water Affairs and Forestry study [42]. Seven scenarios were developed based on variations in demand, supply, treatment requirements and dam operations, as shown in Table 10.

Several policy response options were also considered (see Table 11) and included water conservation and demand management, groundwater augmentation from aquifers, additional surface water supply, reuse of secondary treated effluent, advanced effluent recycling and sea water desalination. The conservation and demand management options were taken from the Department of Water Affairs and Forestry Reconciliation Strategy [43], which estimates that limited measures can achieve savings of 44.8 million m^3/year and extended

[10] By F. Ahjum, A. Hughes and C. Fant, Energy Research Centre, University of Cape Town, South Africa.

TABLE 10. SCENARIO DEFINITIONS, CAPE TOWN

Scenario	Water demand[i]	Water supply[ii]	Water treatment[iii]	Dam waters[iv]
1	High	Historical	Low degradation	Regulated
2	High	Historical	Low degradation	Unrestricted
3	High	Reduced	High degradation	Regulated
4	High	Reduced	High degradation	Unrestricted
5	Low	Historical	Low degradation	Regulated
6	Low	Historical	Low degradation	Unrestricted
7	Low	Reduced	High degradation	Regulated

i High assumes high economic and population growth. Low refers to lower economic and population growth.

ii Historical refers to historical average surface water inflows. Reduced assumes 15% lower surface water inflow during 2016–2025 and 25% lower inflow during 2026–2030 relative to historical averages.

iii Low degradation assumes conventional treatment only is required. High degradation assumes conventional plus ultra-filtration and brackish water reverse osmosis is required.

iv Regulated indicates that the use of dam water is regulated within specific annual limits to maintain long term storage levels. Unrestricted refers to the unrestricted use of dam water.

TABLE 11. INTERVENTION PATHWAYS, CAPE TOWN

Intervention pathway	Water savings from WC/WDM	Groundwater augmentation (TMG–THK)	Additional surface water	Reuse of secondary treated effluent	Advanced effluent recycling	Sea water desalination
(a)	Limited (45 million m^3/a)	X		X		X
(b)	Limited (45 million m^3/a)	X	X	X	X	

TABLE 11. INTERVENTION PATHWAYS, CAPE TOWN (cont.)

Intervention pathway	Water savings from WC/WDM	Groundwater augmentation (TMG–THK)	Additional surface water	Reuse of secondary treated effluent	Advanced effluent recycling	Sea water desalination
(c)	Extended (106 million m^3/a)			X		X
(d)	Extended (106 million m^3/a)	X		X	X	

Note: TMG–THK — Table Mountain Group–Theewaterskloof; WC/WDM — water conservation and water demand management.

measures 106 million m^3/year. The groundwater augmentation options involve tapping underground aquifers. The additional surface water options include five separate measures to divert surface water or augment existing dams. The water reuse, recycling and desalination options are modelled as a set of technologies to reuse effluent or desalinate brackish water at different volumes and energy requirements for treatment and pumping.

The various scenarios and policy response option combinations were evaluated in terms of energy intensity (energy per unit of water delivered), a water supply reliability index (indicating the percentage of the year during which water demand is met) and a system storage index (the ratio between the storage in dams at the end and beginning of the hydrological year). A combined ‘performance index’ was calculated as the combination of these factors, equal to (water supply reliability) × (system storage index)/(energy intensity).

As mentioned, a further analysis was conducted on the effect of relocating horticulture in the Cape Town municipality to another (warmer and drier) area which would require additional irrigation.

II.6.4. Selected findings and conclusions

A full set of results for various combinations of the scenarios and intervention pathways is shown in Table 12 (excluding the results for relocating horticulture). The results indicate that Cape Town’s water system is vulnerable to high water demand growth combined with climate change impacts that would reduce water inflows into the system (i.e. high demand/reduced water supply scenarios 3 and 4). Under these conditions, the performance index declines significantly without policy intervention. While sea water desalination (interventions (a) and (c)) can increase system reliability, it also increases energy intensity so the overall impact on the performance index is limited. On the other hand, other interventions (such as extended conservation, effluent recycling — interventions (b) and (d)) achieve the highest performance index across a range of scenarios. In any case, a variety of policy interventions are likely to be required to ensure a safe and secure water system in the future.

TABLE 12. ANALYSIS RESULTS, CAPE TOWN

Intervention	Scenario	Indicator			
		Energy intensity ($kW \cdot h/m^3$)	Reliability index	System storage index	Performance index
None	1	0.61	49	0.77	61.9
	2	0.58	85	0.31	45.4
	3	0.63	48	0.48	36.6
	4	0.59	80	0.24	32.5
	5	0.61	78	0.93	119.0
	6	0.59	100	0.86	146.0
	7	0.62	76	0.87	107.0
(a)	1	1.01	84	0.97	80.7
	2	1.00	99	0.97	96.0
	3	1.06	84	0.61	48.3
	4	1.03	99	0.48	46.1
(b)	1	0.73	89	0.96	117.0
	2	0.72	100	0.99	137.5
	3	0.76	87	0.31	35.5
	4	0.73	98	0.29	38.9

TABLE 12. ANALYSIS RESULTS, CAPE TOWN (cont.)

Intervention	Scenario	Indicator			
		Energy intensity (kW·h/m^3)	Reliability index	System storage index	Performance index
(c)	1	0.96	92	1.00	95.8
	2	0.95	100	0.99	104.2
	3	0.98	89	0.78	70.8
	4	0.96	100	0.56	58.3
(d)	1	0.66	91	0.96	132.4
	2	0.65	100	0.98	150.8
	3	0.69	90	0.68	88.7
	4	0.67	100	0.44	65.7

II.7. SUMMARY: SYRIAN ARAB REPUBLIC

II.7.1. Introduction

This summary is based on the final CRP report The Impact of Environment, Water Resources and Land Protection on the Development of Syrian Energy Supply Strategy.[11]

II.7.2. Situation assessment

The Syrian Arab Republic faces a number of challenges relating to CLEW. The country receives relatively little rainfall, particularly in the arid south-east region, and current water consumption is unsustainable. The impacts of climate change are expected to exacerbate the existing water deficit (see Table 6), with

[11] By H. Omar and M.K. Seif Al-Din, Energy Planning Group, Nuclear Engineering Department, Atomic Energy Commission of the Syrian Arab Republic.

summer temperatures expected to increase by 3.7°C while precipitation is expected to decline by 20–30% over the next 30 years [28]. Increasing agricultural and industrial demand for water (including in the power sector) will place additional stress on water resources. At the same time, economic development will likely necessitate a substantial expansion of electricity generation, requiring additional water for cooling power plants and potentially generating additional GHG emissions. Addressing water needs may also require the increased deployment of energy intensive desalination, further increasing energy needs.

II.7.3. Methodology and scenarios

The study first developed projections of energy and water demand, along with climate change impacts to 2050, which were then combined to construct a range of scenarios to explore alternative strategies for a sustainable climate–energy–water future. Future energy demands were projected with MAED based on assumptions on key parameters such as population growth and density, economic development, mobility requirements and modal choice, industrial growth and other factors [19]. Similarly, MAWD was used to project future water demands based on the same social and macroeconomic drivers, along with assumptions on technical parameters, losses and irrigation needs. However, water demands directly related to the energy sector (i.e. oil and gas production and refining, electricity generation) were estimated separately based on the energy projections. Overall, agriculture consumes the largest share of water, followed by much smaller shares for the residential sector and mining and manufacturing. The study also took into account IPCC estimates of the impacts of climate change on the environment of the Syrian Arab Republic [28], and the increased temperatures and declining precipitation is expected to result in higher electricity demand (e.g. for space cooling, water pumping and desalination) and lower water availability.

These projections of energy and water demand and climate change were combined to construct a reference scenario (RF_SC) and an alternative scenario (Alt_SC), which includes new short lifetime crops from 2015, and higher water supply efficiency in the industrial, service and residential sectors. Three additional policy variants were developed for each scenario:

(1) A carbon tax case, which also provides for the option to deploy lower carbon options such as integrated coal gasification combined cycle (IGCC) power plants with and without carbon capture and sequestration (CCS);
(2) A desalination quota case to examine the response of the electricity generation sector to the introduction of desalination plants;

(3) A water price case to examine the sensitivity of the electricity generation sector to increased cooling water costs.

MESSAGE was used to identify optimal technology and resource pathways to 2050 to meet the energy demands in the scenarios, subject to energy and water resource limits, along with financial and environmental constraints [44].

II.7.4. Selected findings and conclusions

As shown in Fig. 4, in the reference scenario water consumption for power generation climbs from 55 billion m^3 in 2010 to around 440 billion m^3 in 2050. This is driven by growth in demand for electricity (in turn driven primarily by a ninefold increase in economic output) combined with an increasing role of water intensive coal and fossil steam (fuel oil) power plants in the later periods. Nonetheless, power generation accounts for a relatively minor share of total water demand in 2050, with agriculture accounting for about 85% and municipal demand 10.6%.

Table 13 compares results from the reference scenario and several policy variants. The reference scenario has the lowest average cost of electricity, while the desalination and water price variants have the highest costs. The highest cooling water requirements per MW·h occur in the reference scenario and IGCC_CCS (carbon tax case with IGCC and CCS) and desalination cases, with the lowest water requirements per unit in the IGCC (carbon tax with IGCC) and water price variants. Unsurprisingly, the IGCC_CCS case shows the lowest carbon intensity, while the reference scenario and desalination case have the highest CO_2 intensity.

The results help to illustrate trade-offs between energy affordability, water consumption and climate change. For instance, lower water and carbon intensities in the power generation sector are achieved at the expense of affordability; conversely, the lowest carbon intensity (in the IGCC_CCS case) coincides with the highest water requirements. Despite these results, it is also important to keep these findings in perspective, given that the amount of cooling water used in the power generation sector is far below municipal and agricultural demands — for instance, the water savings in the alternative scenario (Alt_Sc) are four times larger in 2050 than the entire water consumption for power generation (see Fig. 4), indicating that the most efficient options to reduce overall water consumption likely exist outside the energy sector. This further illustrates the advantages of the integrated CLEW approach in considering multiple sectors and resources.

TABLE 13. SELECTED SCENARIO INDICATORS FOR ELECTRICITY, SYRIAN ARAB REPUBLIC

	Scenario and policy variants				
	Reference	IGCC	IGCC_CCS	Desalination	Water price
Average cost (US $/MW·h)	71	77	79	89	98
Water consumption, 2050 (m^3/MW·h)	1.31	1.19	1.32	1.31	1.22
CO_2 intensity, 2050 (kg/MW·h)	571	526	332	572	572

II.8. SUMMARY: THAILAND

II.8.1. Introduction

This summary is based on the final CRP report Climate–Energy–Water–Land Linkages for Thailand.[12]

II.8.2. Situation assessment

Thailand aims to significantly increase the production and use of biofuels to reduce GHG emissions and dependence on petroleum fuels. Under the Second Alternative Energy Development Plan (AEDP) [45], Thailand is seeking to produce 9 million L/day of ethanol from sugarcane (63% of the goal) and cassava (37% of the goal) by 2021. This complements existing goals to produce 10.2 million L/day of biodiesel from palm oil (70% of the goal) and jatropha (30% of the goal). However, these biofuel goals will increase competition for agricultural land along with water and fertilizer requirements. Accordingly, this study sought to evaluate the trade-offs between energy, water, land use and climate change associated with alternative biofuel production policies to identify more sustainable options for Thailand.

[12] By S. Wattana, Department of Electrical and Computer Engineering, Faculty of Engineering, Naresuan University, Thailand.

II.8.3. Methodology and scenarios

A set of future scenarios was constructed and analysed using three models representing land, energy and water use:

(1) GAEZ to assess potential biofuel crop yields and land suitability [20];
(2) LEAP for energy use;
(3) CROPWAT/CLIMWAT to determine water use and irrigation requirements [21, 22, 46].

GAEZ and CROPWAT/CLIMWAT account for the different water requirements and suitability in different regions of Thailand of the main biofuel feedstock options (sugarcane, cassava, oil palm, jatropha). These models show, for example, that more land is suitable for growing cassava and jatropha, since jatropha is drought resistant and has the ability to grow in low quality soils. Potential competition is also identified: oil palm is primarily grown in the south, which also overlaps with the most suitable areas for growing sugarcane. At the same time, variations in yields are considered, with maximum yields ranging from 2.43 t/ha for jatropha up to 8.2 t/ha for sugarcane.

A baseline scenario was constructed with key demographic, macroeconomic and agricultural production and consumption assumptions. The baseline also includes the existing biofuel production goals — outlined above — that are expected to substitute 44% of the petroleum used under BAU conditions. Additional scenarios were developed to explore alternative ways to meet the biofuel production goals of the AEDP. The scenarios are shown in Table 14. Each scenario was then evaluated in terms of the following indicators:

- Agriculture: land requirements, quantities of sugarcane, cassava, oil palm and jatropha required and fertilizer requirements;
- Energy: displacement of oil imports and energy balance of biofuel production;
- Environment: changes in CO_2 emissions;
- Water: total crop water requirements and irrigation requirements.

II.8.4. Selected findings and conclusions

Within the ethanol theme scenarios, it is difficult to compare the direct impact of alternative ethanol feedstock options because the EthS and EthC scenarios also assume a reduction (to zero) in the production of cassava and sugarcane, respectively, for purposes other than ethanol synthesis. Given that Thailand is a significant producer of sugar and a large exporter of dried

TABLE 14. BIOFUEL SCENARIOS BY THEME, THAILAND

Scenario	Abbreviation	Detailed description
Ethanol theme		
Ethanol produced from sugarcane and cassava	EthSC	9 million L/day of ethanol, 63% produced from sugarcane and 37% from cassava
Ethanol produced from sugarcane only	EthS	9 million L/day of ethanol entirely produced from sugarcane
Ethanol produced from cassava only	EthC	9 million L/day of ethanol entirely produced from cassava
Biodiesel theme		
Biodiesel produced by oil palm and jatropha	BioOJ	10.2 million L/day of biodiesel, 70% produced from oil palm and 30% from jatropha
Biodiesel produced by oil palm only	BioO	10.2 million L/day of biodiesel entirely produced from oil palm
Biodiesel produced by jatropha only	BioJ	10.2 million L/day of biodiesel entirely produced from jatropha

cassava, these assumptions alone significantly reduce the need for water, fertilizer and energy, along with GHG emissions in the EthS and EthC scenarios, irrespective of the choice of feedstock for ethanol production. The results are detailed in Table 15.

TABLE 15. KEY ETHANOL THEME SCENARIO RESULTS, THAILAND, 2021

	EthSC scenario	EthS scenario	EthC scenario
Total production (million t)			
Sugarcane	106	125	0
Cassava	34	0	49

TABLE 15. KEY ETHANOL THEME SCENARIO RESULTS, THAILAND, 2021 (cont.)

	EthSC scenario	EthS scenario	EthC scenario
Production for ethanol (million t)			
Sugarcane	29	47	0
Cassava	9	0	23
Production for other uses (million t)			
Sugarcane	77	77	0
Cassava	25	0	25
Increase in land requirements (thousand ha)	670	541	1 124
Fertilizer requirement (thousand t)	397	352	136
Crop water requirement (million L)	35 807	23 449	22 328
Irrigation requirement (million L)	16 830	10 703	10 881
Crude oil import (million L)	28 343	28 311	27 156
Net energy balance (TJ)	(10 007)	(8 910)	29 846
CO_2 emissions (thousand t)	93 053	92 971	90 060

For the biodiesel theme, the BioO and BioJ scenarios assume a reduction to zero in the production of jatropha and oil palm, respectively, for purposes other than biodiesel synthesis. While jatropha is not significantly used for other purposes in Thailand, oil palm is a major crop, so this assumption significantly reduces water, fertilizer, energy and GHG emissions in the BioJ scenario independently of the choice of biodiesel feedstock. Accordingly, direct comparison of the impact of feedstock choice is only possible between the BioOJ and BioO scenarios. The BioOJ scenario results in an increase of land use for agriculture of almost

3 million ha by 2021, compared with only 1 million ha in the BioO scenario. This lower land footprint in the BioO scenario leads to lower fertilizer requirements, despite jatropha requiring less fertilizer per hectare (ca. 141 kg/ha compared to 418 kg/ha for oil palm) and lower water requirements. These results are detailed in Table 16. The BioO scenario also shows a reduction in crude oil imports and CO_2 emissions relative to the BioOJ scenario, and a larger improvement in the net energy balance.

TABLE 16. KEY BIODIESEL THEME SCENARIO RESULTS, THAILAND, 2021

	BioOJ Scenario	BioO Scenario	BioJ Scenario
Total production (million t)			
Oil palm	24	30	0
Jatropha	4	0	15
Production for biodiesel (million t)			
Oil palm	16	22	0
Jatropha	4	0	15
Production for other uses (million t)			
Oil palm	8	8	0
Jatropha	0	0	0
Increase in land requirements (thousand ha)	2 912	1 058	7 745
Fertilizer requirement (thousand t)	841	679	1 089
Crop water requirement (million L)	40 936	23 332	79 614
Irrigation requirement (million L)	14 832	9 658	25 557
Crude oil import (million L)	27 953	27 284	29 225

TABLE 16. KEY BIODIESEL THEME SCENARIO RESULTS, THAILAND, 2021 (cont.)

	BioOJ Scenario	BioO Scenario	BioJ Scenario
Net energy balance (TJ)	41 204	63 642	(1 509)
CO_2 emissions (thousand t)	90 914	89 229	90 060

Despite the idiosyncrasies of the scenario assumptions in the study, the results demonstrate that the choice of bioenergy crops to meet biofuel targets affects land use, fertilizer, total crop water and irrigation requirements, as well as oil imports, CO_2 emissions and the net energy balance [47–49]. Moreover, the growing demand for bioenergy crops can impact land use for food and cash crop cultivation. The limitations of this study highlight the need for careful scenario definition to ensure the results remain of high value to decision makers.

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ABBREVIATIONS

BAU	business as usual
CCS	carbon capture and sequestration
CHP	combined heat and power
CLEW	climate, land, energy and water
CRP	coordinated research project
(G)AEZ	(Global) Agroecological Zones
GDP	gross domestic product
GHG	greenhouse gas
IGCC	integrated coal gasification combined cycle
IPCC	Intergovernmental Panel on Climate Change
LEAP	Long-range Energy Alternatives Planning
MAED	Model for Analysis of Energy Demand
MAWD	Model for the Analysis of Water Demand
MESSAGE	Model for Energy Supply Strategy Alternatives and their General Environmental Impacts
SAPWAT	South African Procedure for Estimating Irrigation Water Requirements
SDG	Sustainable Development Goal
WEAP	Water Evaluation and Planning System
WESAT	Cape Town Water Energy System Analysis Tool

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