

Integrated climate, land, energy, and water framework to support the Nationally Determined Contribution updating process

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ABSTRACT

System models help policymakers to produce net zero decarbonization pathways. In 2019, Costa Rica launched its National Decarbonization Plan (NDP) – constructed using a detailed Open-Source energy Modelling System (OSeMOSYS-CR) model and simplified ones for non-energy sectors. The country then developed an integrated Climate, Land, Energy and Water (CLEW) model to capture synergies across sectors and guide future climate related processes. This resulted in the CLEW-CR model. In 2020, the country updated its Nationally Determined Contributions (NDCs), deploying a highly participatory process supported by the CLEW-CR model to guide the discussions with over 150 stakeholders. This paper presents the framework adopted to develop the CLEW-CR model (from data collection to scenarios creation and cost-benefit analysis) and describes its use to align its NDCs with its NDP. Over 15 different scenarios were produced to inform the country's dialogue during the updating process of its NDCs demonstrating the flexibility of this model to support multiple policy questions. This paper shows that deploying the NDC by 2030 and the NDP by 2050 would result in a net economic benefit of \$55 billion – about 85 % of Costa Rica's GDP, highlighting the economic viability of Costa Rica's commitment to a sustainable future.

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1. Introduction

Article 4 of the Paris Agreement calls upon countries to design Long-Term Strategies (LTS) to reduce greenhouse gas (GHG) emissions. LTS are an ongoing climate and development planning process that sets long-term goals and directs short-term decision-making to decarbonize economies [1]. To this end, many actors must adopt measures across many sectors to transform the economy and reduce emissions without hindering economic growth [2], i.e., decarbonizing the economy. The

Glasgow Pact, signed in COP26, re-states the need for countries to have an LTS and strongly suggests using the latest science and advanced tools for their design or update [3]. As the decade of 2020 advances, countries will update their Nationally Determined Contributions (NDCs) every five years, outlining their efforts to reduce GHG emissions and adapt to the impacts of climate change [4]. Hence, governments around the globe are and will be linking LTS and NDCs in the near term because they will have to reach significant milestones by 2030 (reflected in their NDCs) to keep the global average temperature below 2 °C and as close as to 1.5 °C above pre-industrial levels [5].

Defining commitments in the NDC that will help a country reach the objectives set out in its LTS is a collaborative process involving the public, private, and non-governmental sectors. The process must also reflect equity among developed and developing nations [1]. Indeed, the private sector will implement most of the investments needed to decarbonize the economy. While formulating NDCs for development and climate action plans, policymakers and stakeholders commonly discuss how much investment is necessary and whether the return on these

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investments will be positive. Thus, policymakers need models to understand the impact of short and mid-term actions on the long-term transformations required in the economy. These models need to be transparent to the public so that stakeholders trust the soundness of the plans and can then execute actions with a clearer understanding. In practice, the academic sector develops and maintains these models, given their access to resources, deep theoretical knowledge, and commitment to rigorous research. Academia continually updates the models and invites scrutiny from the broader research community to achieve improvements.

Costa Rica is one of the first countries to have submitted an LTS to the United Nations Framework Convention on Climate Change (UNFCCC): its National Decarbonization Plan 2018–2050 (NDP) [6]. The strategy is "1.5 °C compatible" [7], making it a case study of interest, considering the aggregation of climate plans is insufficient to meet the Paris Agreement's goal [8]. In 2020, the Ministry of Environment and Energy (MINAE), through the Climate Change Directorate (DCC), updated the country's NDC [9]. The DCC led the expansion of an existing energy model, OSeMOSYS-CR [10], based on the Open-Source Energy Modelling System (OSeMOSYS) [11].

This paper describes the resulting extended model, which follows a Climate, Land, Energy, and Water (CLEW) nexus [12] approach. Initially used for scenario analysis and accounting costs and emissions from the energy sector, the model presented here (henceforth, CLEW-CR) incorporates mitigation measures in the agriculture, forestry, land-use (AFOLU), and wastewater sectors. To do so, the CLEW-CR represents different supply chains to satisfy water and food demands. OSeMOSYS is an appropriate framework for CLEW-CR because of its modularity and flexibility in representing diverse technologies in an integrated manner [12]. Moreover, the paper exemplifies how a developing country like Costa Rica can and should develop its capacity to assess its own LTS and NDCs.

The model CLEW-CR was produced to achieve a more comprehensive economic assessment of policy measures by representing the interactions between energy, land use, and water in a highly integrated manner [13]. The resulting integrated system representation can capture synergies between mitigation and adaptation policies. These models may help to design policies that avoid inconsistencies across sectors [14] and, on the contrary, pursue actions that advance mitigation across multiple sectors [15]. Furthermore, CLEW modelling enables analysis that considers various in-depth interactions and implications on a long-term horizon [16], including the study of economic and technical aspects of policies.

Despite the growing emphasis on integrated environmental and energy modelling, there remains a gap in detailed, practical applications of such models. The model CLEW-CR resulted from a participatory process involving many stakeholders that provided input to define the model structure, populate the model with data, and co-design the scenarios. This case study can guide building and applying CLEW models in the practical context of updating an NDC, allowing other countries to emulate the Costa Rican experience. To the best of the authors' knowledge, no practical example in the literature guides NDC updates with CLEW models in Latin America and the Caribbean (LAC) region. The paper describes a Business-As-Usual scenario (BAU) and a decarbonization scenario (NDP, which refers to the National Decarbonization Plan) used to inform the NDCs. The scenarios and the modelling framework were co-created in multiple stakeholders-driven participatory processes for all the sectors included in the model.

This paper contributes to the existing literature by providing a practical example of how CLEW models can be effectively applied to update NDCs. The Costa Rican case study, detailed in this paper, fills this gap by demonstrating how interdisciplinary collaboration, participatory processes, and the CLEW framework can be leveraged to achieve comprehensive and actionable insights for NDC updates. This approach is novel in its application and serves as a valuable guide for other countries in the region, highlighting considerations needed to integrate

the CLEW nexus in their environmental and energy planning processes.

This paper is structured as follows. Section 2 outlines the process to implement CLEW modelling for an NDC update, consisting of five steps: (i) Background and policy identification, (ii) model design, (iii) scenario design, (iv) reporting and divulgation, and (v) updating. Section 3 discusses how to make a CLEW model practical from the beginning of a project through strong stakeholder coordination and engagement. Section 4 describes the components of CLEW-CR. Section 5 characterizes the scenarios, Section 6 presents the results, and Section 7 discusses them. Section 8 concludes the paper.

2. The climate land energy water (CLEWs) nexus for policymaking support

Universities and organizations have developed CLEW models with diverse objectives and scopes (e.g., local, urban, national, regional, and global). Examples include Kenya [17], Nigeria [18], Bolivia [19], Mauritius [20], Sweden [21–23], Eastern Africa [24], and more [25]. These models support the following activities [25]: policy assessment, identifying technology deployment needed to achieve policy goals, assessment of resource management and efficiency, and identifying opportunities for international cooperation and collaboration.

More than 20 CLEW models with a nationwide scope, using the OSeMOSYS framework, have been developed worldwide. However, few models involve the assessment of NDCs or similar climate policy documents. In 2018, the United Nations Economic Commission for Africa (UNECA) commissioned the development of CLEW Nexus modelling frameworks in Sierra Leone and Ethiopia [25,26]. These studies considered the land, energy, and water nexus at a national scale. They evaluated the implications of implementing each country's NDC with a model based on the OSeMOSYS framework. These two studies were the first two CLEWs models created to support NDCs [25]. In Ethiopia, the study gave key findings about trade-offs, synergies, opportunities, and recommendations for strategies and policy direction for achieving the NDC.

Besides OSeMOSYS, other modelling frameworks can provide valuable insights into the interactions between land and water resources. These include the integrated WEAP [27] and LEAP systems from the Stockholm Environment Institute, which focus on the close links between water and energy systems; the European Commission's CAPRI model [28], which evaluates agricultural policy impacts; E3ME-FIT [29], a macro-econometric model exploring interactions between the energy, economic, and environmental systems; and the IMAGE [30] framework, assessing global environmental changes concerning societal dynamics.

Every country and region have specific geographic, political, environmental, and socioeconomic realities. CLEW models are flexible and adaptable to capture this diversity, with the ability to incorporate data and scenarios gathered through a participatory process. Through the involvement of decision-makers and other stakeholders, modelling teams can receive data and co-create scenarios for analysis. This work differentiates from other examples in the literature by the participatory approach used to build the land, energy, and water nexus into CLEW-CR and apply the model to update the NDC. The CLEW-CR development and application followed these steps:

- First, the entity in charge of updating the NDC (the DCC, in the case of Costa Rica) coordinates with a local academic team to organize workshops and bilateral meetings to develop the model and the scenarios to be analysed (see Section 3). Costa Rica was able to implement this approach because of the capacity and skills available at the UCR, a public institution that has been able to self-sustain a modelling team [31].
- Second, the academic team builds the CLEW model, following the process in Section 4.

- Third, in collaboration with a stakeholder working group, the modelling team and the DCC lead the co-creation of scenarios implemented in the model; the result of this process is in Section 5.

3. Making the CLEW model practical for the NDC update

The experience of Costa Rica and other international experiences in the literature suggest that a locally produced model, nurtured by stakeholder participation, reduces the chance of building a model with missing elements and interactions. The DCC and the modelling team gathered the following elements: barriers, interactions between sectors, availability of resources, applicable international agreements and policy documents, plans, regulations, and currently planned mitigation actions. These elements defined the CLEW model's scope.

Workshops enabled experts to describe their sectors in detail and start a communication bridge between the participants (academia, civil society, non-profit organizations, private entities, and international organizations) and the modelling team at UCR for data gathering, defining modelling priorities, and clarifying any data ambiguity. A diverse and broad stakeholder group is part of the best practices for developing or updating NDCs [32]. Table 1 shows the workshops (three) and bilateral meetings (seven) carried out throughout the process. In every interaction opportunity, sectoral experts transferred knowledge to the modelling team.

In the first workshop, the participants collaborated to identify ongoing or planned GHG mitigation actions. Not surprisingly, the main discussion revolved around the National Decarbonization Plan, Costa Rica's main climate policy document. The stakeholder working group was divided into four subgroups or clusters: (i) agricultural sector, forestry, nature, water, and oceans; (ii) industrial sector, construction, and management of waste sectors; (iii) transport and urban development; and (iv) energy sector. During the workshops, each cluster worked on creating exploratory scenarios in a participatory manner with various people from multiple sectors of the country. These 18 scenarios contemplated the evolution of variables between optimistic and pessimistic futures related to climate action and sustainable development.

The strategy for updating the NDC contemplated *planning based on assumptions as the general methodological framework to systematically integrate quantitative and qualitative approaches*. In addition, the participatory creation of future exploratory scenarios complements the quantitative analyses and strengthens the climate plans and policies supporting the NDC. The updating process consisted of two phases: (i) creating exploratory scenarios on the future of Costa Rica in 2050 and (ii) formulating recommendations to strengthen the climate action lines

Table 1
Workshops' objective and quantity of participants.

	Objective	Number of participants
First Workshop	• Delimitation of the study • Identification of sources of information, plans, and actions that are promoted at the national level to mitigate greenhouse gases.	21 participants
Second Workshop	• Data gathering. • Review the constraints and assumptions. • Discussion of the structure of the model • Discussion of the preliminary results	22 participants
Bilateral meetings	• Identify missing information • Gathering of specific information • Discussion of the model structure • Discussion of the ambition of decarbonization goals	7 institutions ^a
Third Workshop	• Present the CLEW model framework and its results.	29 participants

^a Including Water Directorate (DA), National Forest Financing Fund (FONA-FIFO), Secretary Reduction of Emissions due to Deforestation and Forest Degradation (REDD + Secretariat), Ministry of Housing and Human Settlements (MIVAH), Central Bank of Costa Rica (BCCR), Ministry of Health.

in the face of possible future contextual changes. The CLEW-CR modelling framework enforced the second phase by giving quantitative results to the developed scenarios.

The use of the CLEW model in Phase 2 was structured into four work clusters: (i) agricultural sector, forestry, nature, water, and oceans; (ii) industrial sector, construction, and management of waste sectors; (iii) transport and urban development, and (iv) energy sector. During the workshops, each cluster worked on creating exploratory scenarios in a participatory manner with various people from multiple sectors of the country. These scenarios contemplated the evolution of variables between optimistic and pessimistic futures related to climate action and sustainable development. Ultimately, the participants created 18 scenarios considering the evolution of Climate, land, energy, and water variables.

The scenario creation was based on responding to questions about contextual factors that could generate changes in the country by 2050, the implications for achieving our climate goals, and the actions we should take to strengthen the achievement of the lines of action for these goals. In total, four scenarios contemplated energy variables; three scenarios considered Energy and Climate, five scenarios contemplated Climate and Land variables; one scenario considered Land, Energy, and Climate; three scenarios contemplated Land, Water, and Climate variables; and two scenarios, Climate, Land, Energy, and Water variables. The diversity of variables and actions included in the 18 analysed scenarios show the versatility and flexibility of the scenarios we can create in the CLEW-Nexus modelling framework. It also shows how the model allows exploring future uncertainties that could impact the landscape of Costa Rica to 2050 and influence the possibility of achieving climate goals. Table 2 shows a summary of the 18 scenarios. For each sector, we mapped specific variables in each scenario to create discussion around the results. The variables range from land use and crop proportion to emissions related to wastewater for human consumption, electricity generation by source, emissions related to wastewater human consumption, and electricity generation by source.

Throughout this process, the contributions from various stakeholder groups—from academia, government agencies, non-profit organizations, and private sector entities—were instrumental in shaping the model's outcomes. These stakeholders brought invaluable insights and perspectives, enhancing the model's relevance and applicability. For instance, academic experts provided foundational theoretical knowledge, while civil society and NGO representatives offered ground-level insights crucial for understanding real-world implications. Private sector participants contributed practical considerations and feasibility aspects, ensuring that the model's recommendations were environmentally sound and economically viable. On the other hand, international organizations helped align the model with best practices and standards.

This multifaceted approach helped to develop a comprehensive and robust model that accurately reflects the complexities of the climate, land, energy, and water nexus. The iterative process of feedback and collaboration also played a key role in refining the model, ensuring that it is not only scientifically sound but also attuned to the socioeconomic realities of Costa Rica. This collaborative approach, underpinned by active stakeholder participation, was fundamental in achieving a balanced and nuanced understanding of the challenges and opportunities within the CLEW nexus. Consequently, the stakeholder-driven development of the CLEW model serves as a testament to the effectiveness of collaborative research in environmental policymaking, providing a framework that can be emulated in other contexts where multi-dimensional and multi-stakeholder engagement is key to addressing complex environmental challenges.

4. Building the CLEW-CR model

The CLEW-CR model is based on OSeMOSYS, an open-sourced cost optimization software for long-term energy planning [11] but adapted

Table 2
Scenarios to inform the NDC considering a multisectoral approach.

	Cluster Scenario	Cluster 1				Cluster 2					Cluster 3					Cluster 4			
		S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S15	S16	S17	S18
LAND	Land use proportion	x	x	x	x	x	x		x	x		x	x		x				
	Crop production	x	x	x	x	x	x		x	x					x				
	Crops exports	x	x	x	x	x	x		x	x					x				
	Emissions associated with land use	x	x	x	x	x	x		x	x		x	x		x				
WATER	Treated and untreated water					x	x		x	x		x							
	Emissions related to wastewater for human consumption					x	x		x			x							
ENERGY	Electricity generation by source															x	x	x	x
	Electricity demands					x	x												
	Energy consumption by fuel by sector															x	x		x
	Energy demand in the transport sector															x	x		x
	Distribution of passenger demand										x	x							
	Distribution of the private vehicle fleet										x				x				
	Distribution of the public fleet										x	x						x	
	Distribution of the freight fleet													x					
	Emissions associated with transport										x	x		x	x			x	

to represent the land and water sectors. Exogenous demands and constraints are the inputs of the model. The blocks of functionality (each with an associated cost, efficiency, and emission factor) and their interconnections represent supply chains of resources. The blocks of functionality are technologies that consume or produce fuel (these terms are typical of OSeMOSYS modelling [11]). If parameterized well, such supply chains can represent water purification and distribution, electricity generation, crop production, water treatment infrastructure, electric vehicles, and forest land covers.

The model combines 225 technologies and 136 fuels. Technologies include forest coverage, crop coverage, surface water extraction, groundwater extraction, wind power plants, diesel trucks, transmission lines, etc. Commodities include available land, precipitation, generated electricity, diesel, and others (a link with the fully documented model is in Section 9). The number of technologies and fuels was designed with a Reference Resource System (RRS) diagram, representing the interactions between resources, the supply chains, and the final demand per sector. With the RRS, the modelling team defined the data requirements based on the specific information in the modelling framework. Most of CLEW's technical and economic parameters came from Costa Rica's national studies and public institutions, complemented by inputs gathered through stakeholder consultations.

The model includes two different time slices, dry and rainy seasons, which mainly aim to represent the differences in precipitation between these two seasons and the effects this has on the whole land, energy, and water systems. Fig. 1 presents a simplified version of the general framework of CLEW-CR: land (green, bottom right), energy (orange, top), and water (blue, bottom left), and the linkages among them. The subsections below describe the land and water submodels in more detail. Previous works and papers have extensively documented the energy submodel [10,29,30]. Crucially, the submodels are executed independently and linked through consistent parameters.

We gathered data from multiple sources to create our model. We combined national studies and public institution data from Costa Rica

with insights from stakeholder consultations to get detailed sector-specific information and clarify uncertainties. If we could not find national data, we used information from academic literature and international market dynamics, policies, and institutional factors.

CLEW-CR accounts for positive and negative externalities. For the land sector, ecosystem services like provision (for example, food and energy), regulation (for example, water quality, climate, erosion), cultural (for example, recreation and tourism), and support (for example, soil fertility and pollination) are included (positive externalities; see model documentation in Section 9). The energy sector's effects on health, congestion, and accidents are included (negative externalities; see Ref. [10]). For the water sector, we included the effects on health (negative externalities; see model documentation in Section 9).

4.1. Land submodel

The land submodel has five main land covers. The REDD + Costa Rican data reports that 60 % of land corresponds to forest coverage for the country, disaggregated into ten different subcategories of forest types (i.e., mangroves, moist, palm, dry, and wet forest, for both primary and secondary categories) [33,34]. The remaining 40 % of land cover is non-forest. It is disaggregated into urban coverage, crops (rice, banana, coffee, sugar cane, palm oil, pineapple, and others) [35–41], grassland (milk and beef production) [35,36,42,43], and other covers (bare land and land without information).

A land-use change module defines the baseline projection of the land cover shares to 2050. This module uses historical information on land-use change transition matrixes from 2000 to 2015, including changes in every forest type [29]. To estimate the transitions between coverages, we used the average of all available historical transition matrixes to define the change between one year and the following (i.e., Markov Chains). This same module quantifies land-use change emissions and CO₂eq removals according to the age of the forest (defined in age cohorts), the changes in carbon stock, and the overall results of the

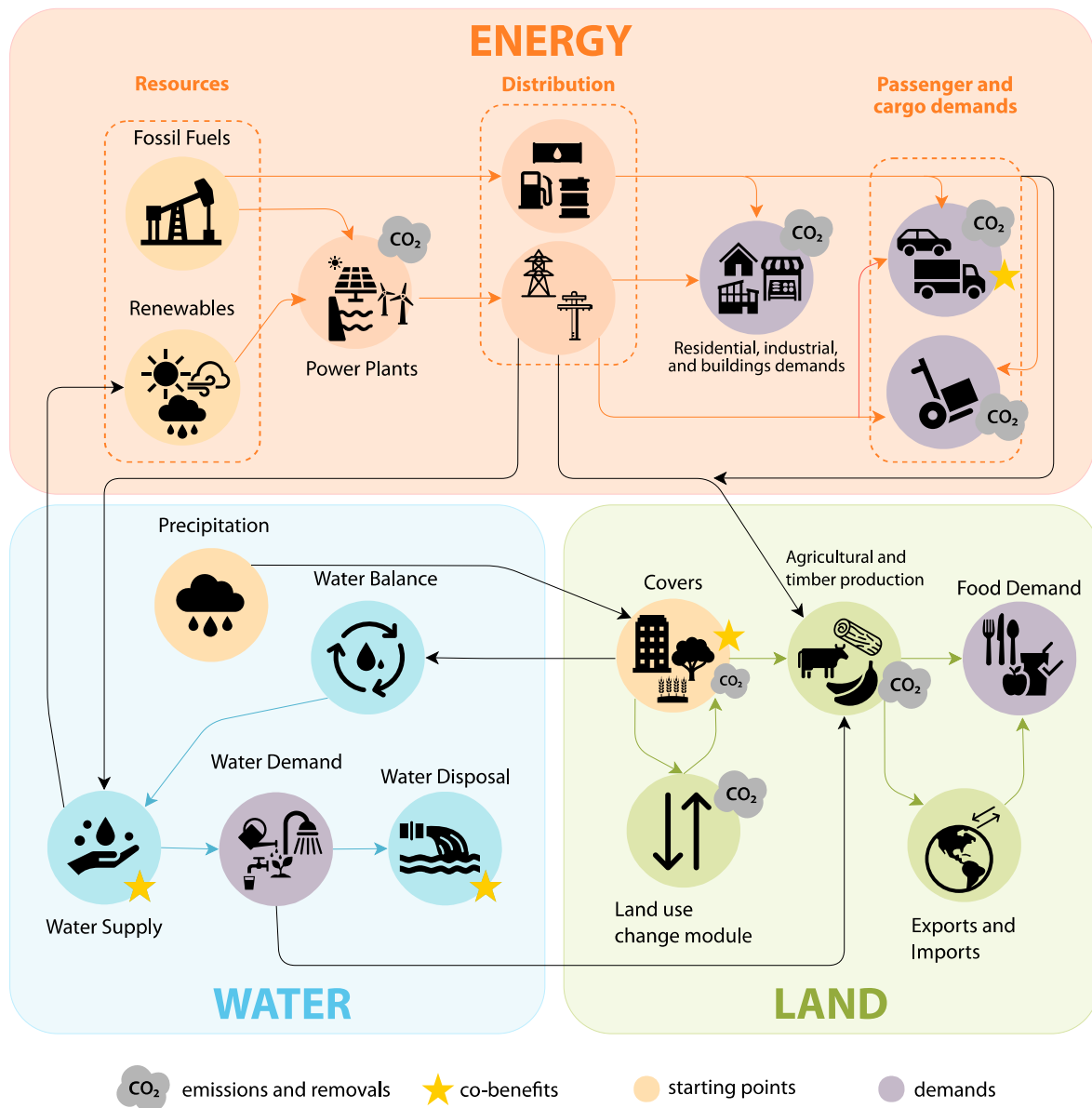


Fig. 1. The submodels of the CLEW-CR model.

land-use distribution.

The land submodule represents supply chains for agriculture (e.g., meat, milk, bananas, sugar, oil palm, among others) and forest production systems (e.g., wood) [35]. In this context, land use is conditioned by, for the most part, national and international market forces, policies, demands, and institutional factors [44]. Data on yield, lifetime, residual capacity, and costs were obtained from national data sources and academic literature [38,39,41,45–50]. Besides including a local demand for every agricultural and forest production considered, the model includes imports and exports [3]. The activity of these production schemes accounts for the emissions related to crops, livestock, and forest plantations [33,51,52].

4.2. Water submodel

The water submodel reflects the hydrological processes of the water cycle and water uses since it links the water offered to its demand and disposal. Costa Rica is a country that depends entirely on precipitation; therefore, this is considered the primary input of the model. The return of water flows that remain after water is consumed is also part of this

resource availability. Precipitation and land cover types determine the water supply and the resulting water balance (i.e., the share between evapotranspiration, water run-off, and underground recharge). Considering the water availability, water is extracted from surface and groundwater sources. After that, drinking water, irrigation water, and other water uses are produced to meet the needs of the specific sectors considered in the model. The model represents the water distribution network and considers its losses in the distribution process. The model also considers the benefits of reducing water losses.

CLEW-CR considers three water demand components: i) agriculture (crops and livestock activities linked to the land use model), ii) human consumption (drinking water for the residential sector), and iii) industry and services (commercial and tourism activities). In the case of the agricultural sector, water is distributed by concessions and irrigation channels. Regarding industrial demand, water is supplied by both the distribution network and concessions. As well as this, sanitation considerations are a key aspect of the water model. The water framework includes sewerage (with and without water treatment plant connections), septic tanks, and water without sewerage and treatment in its structure. The model differentiates between urban and rural areas

because Costa Rica's sanitation goals are established in those categories. Industrial wastewater disposal is separated between treated and untreated water, allowing emissions quantification for each disposal scheme. Also, the health benefits of sanitation account for reduced health expenses since water treatment infrastructure increases.

5. Scenario design

While there were 18 scenarios explored for the NDC process, here we present the development of two main scenarios: the business-as-usual scenario (BAU) and the decarbonization scenario (NDP, reflecting the National Decarbonization Plan) compatible with zero net emissions of the country by 2050. Through the participatory process, the participants voted from 1 to 5 on the assumptions' validity, and updates were made for assumptions with scores lower than 4, so each scenario was robust enough. One core assumption is that the BAU and NDP share social and economic demands, but the technological supply chains differ. In the following sections, we provide a brief overview of the narratives that influenced the parametrization of both scenarios.

5.1. Water submodel

National Plan for the Integrated Management of Water Resources (PNGIRH) [53] is the primary reference for creating the scenarios. In the BAU scenario, the future value of the variables is based on current trends. Water availability is almost the same for the BAU and NDP scenarios since the exogenous projections were obtained using the same climate model, RCP 8.5 [54]. The land cover determines the level of evapotranspiration, surface run-off, and aquifer recharge. Of the total rainfall, 41 % in forest cover becomes evapotranspiration, 42 % in surface run-off, and 17 % in aquifer recharge. For crops, evapotranspiration corresponds to 42 %, surface run-off is around 46 %, and aquifer recharge is 12 %. Fig. 2 shows the policy targets defined in the participatory process for the NDP scenario. These values are external inputs that contribute to the storyline of each scenario. The values were discussed during the workshops; some are derived from existing policies. More detailed assumptions are in Supplementary Note 2.

5.2. Land submodel

In the BAU scenario, agricultural and livestock systems maintain their current management trajectory without significant land use planning efforts to regulate these activities towards better performance and reduced emissions. Also, no protection policies are executed on forest coverage or improvement of the performance of agricultural economic activities. Fig. 3 shows the modelled targets for the NDP, deriving from stakeholder consultation and the ambition set by the stakeholders; the NDP did not explicitly include these technical variables in its inception. More detailed assumptions are in Supplementary Note 1.

5.3. Energy submodel

Fig. 4 shows the targets modelled for the NDP scenario. Unlike the other sectors, the energy sector had more quantitative content in the Decarbonization Plan, but further studies [10,55] and the participatory process (described in Section 3) complemented the definition of targets. More details of the energy submodel are in Supplementary Note 3.

6. Results and discussion

This work presented the development of a CLEW model with profound technical detail (see Supplementary Notes 1, 2, and 3) that reflected the worldviews of a large group of stakeholders. Since the technical analysis was iteratively shared with the stakeholder working groups, who even co-created multiple scenarios, they accepted the emission trajectories and cost metrics. They used them to populate quantitative elements of Costa Rica's NDC. Furthermore, the level of technical detail captured in the scenarios would not have been possible without the interaction with national experts during the participatory process.

This framework can facilitate the generation of various pathways essential for deliberation during updating Nationally Determined Contributions (NDCs). We have successfully achieved this, and here are some of the key outcomes. Emission trajectories are a key model output to inform the NDC. The results shown in Fig. 5 indicate that national

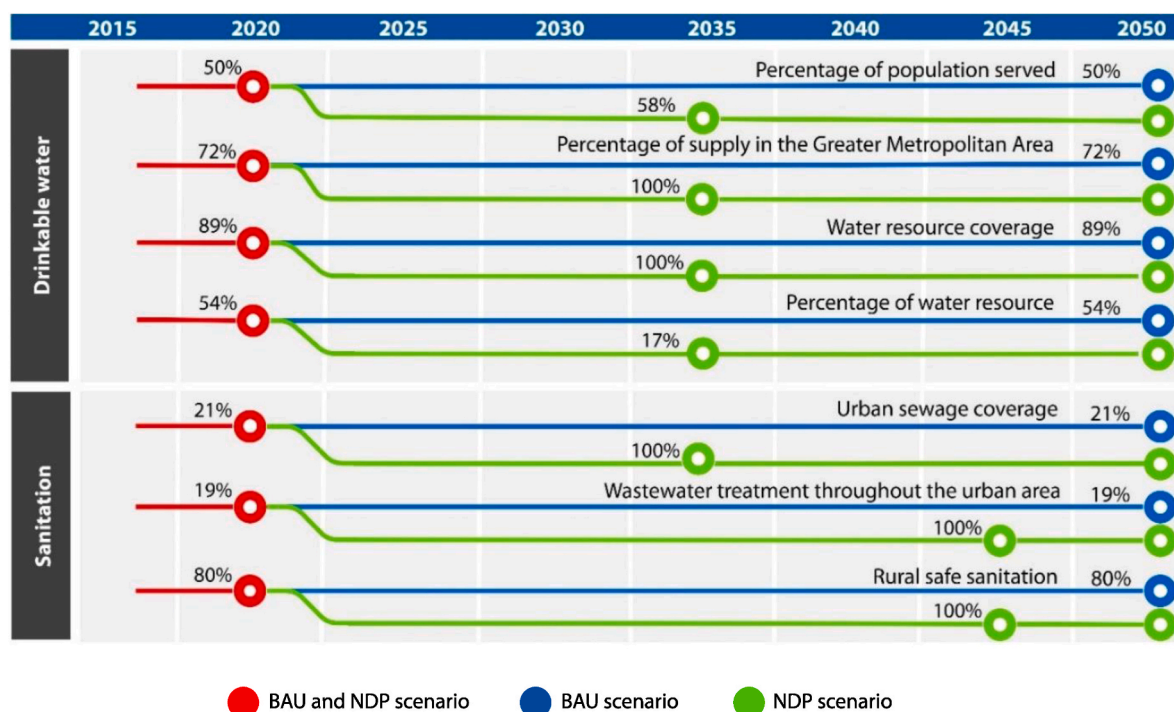


Fig. 2. Synthesis of targets in the NDP scenario for the water submodel.

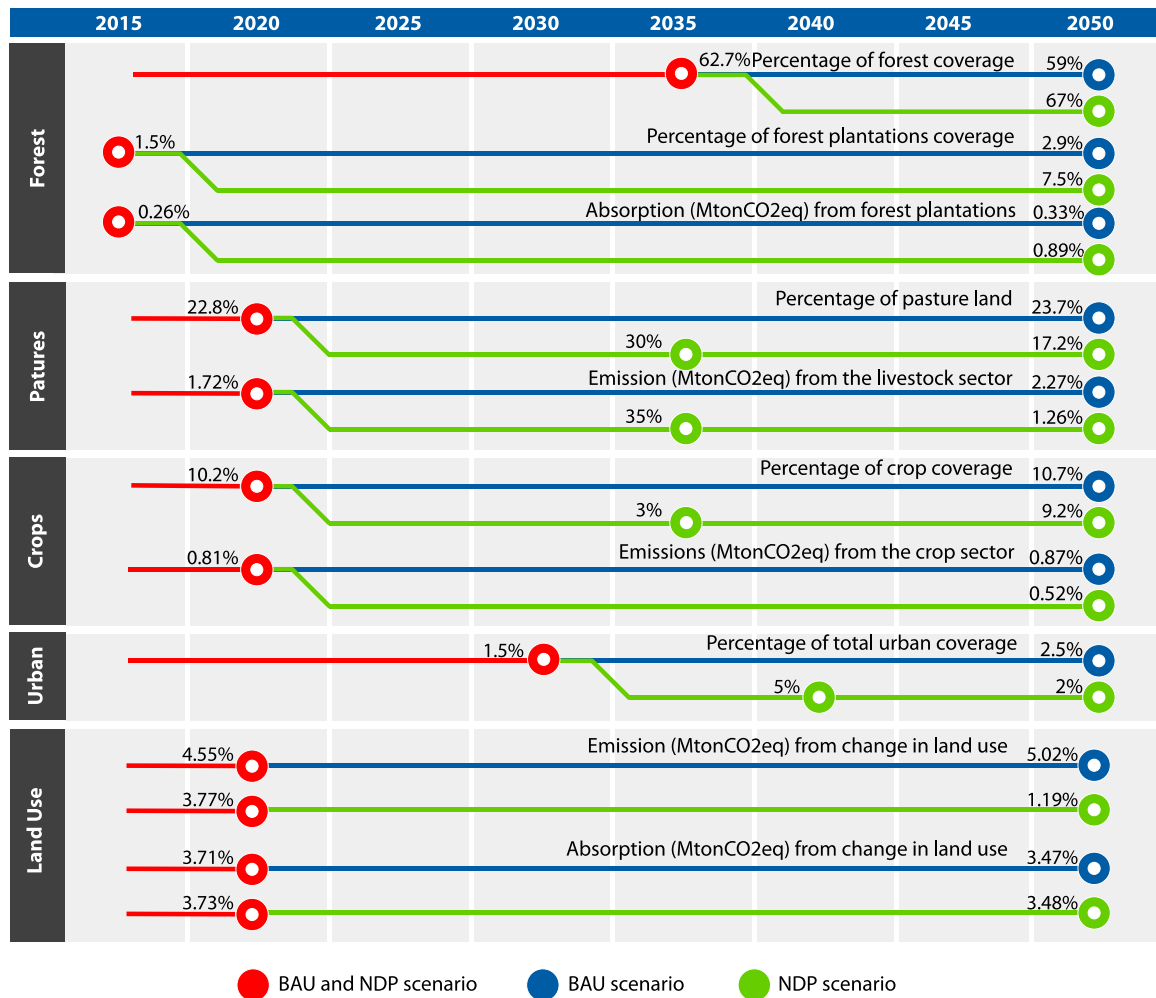


Fig. 3. Synthesis of targets of the NDP scenario in the land submodel.

emissions in 2050 would be 18.4 MtCO₂eq in a BAU scenario and could be reduced to 3.43 MtCO₂eq, considering the successful implementation of the NDP. This trajectory does not consider mitigation actions on the sectors not captured in the model: industrial processes, solid waste management, and some measures in the industrial sector. The emissions of the sectors not included in CLEW-CR are the same in both scenarios. Hence, achieving total net emissions equal to zero requires actions in the sectors not captured in the CLEW-CR model.

Emissions in the energy sector would grow from 6.80 MtCO₂eq to 9.67 MtCO₂eq in the BAU scenario from 2018 to 2050. This scenario incorporates a moderate penetration of solar and wind generation, distributed generation for self-consumption, private electric vehicles, and electric public transport (buses). Additionally, it considers that the patterns of passenger and cargo mobility are maintained throughout the analysis period, which suggests that there is no modal shift, growth in non-motorized mobility, or impact of digitization. For public transport, no changes are incorporated into the system, such as electric passenger or cargo trains, nor the restructuring of the bus system by sectors. Neither is a significant technological change contemplated, the use of storage, or the incorporation of alternative energy sources, such as hydrogen or biofuels.

Conversely, the NDP scenario reduces emissions from 6.80 MtCO₂eq in 2018 to 1.03 MtCO₂eq in 2050. The successful mitigation actions enabled the reduction of almost 85 % of emissions. The mitigation actions primarily focus on the transport sector, where the private, public, and freight sector electrification is considered. Also, the scenario considers the passenger and freight train, hydrogen technologies after 2030,

and the inclusion of fuel mixtures with ethanol and biodiesel. The electricity capacity required to fulfil the electricity crescent demand is obtained from deploying more solar and wind power plants.

The demand for energy in the residential, commercial, industrial, and agricultural sectors has experienced a decrease due to the transition to more efficient devices. For example, this reduction is due to the promotion of electric boilers in the industrial sector and electric cooking technologies in the residential sector. The remaining emissions in 2050 are mainly from diesel consumption in the industry and agriculture subsector and LPG from public and freight transport.

The BAU scenario emissions in land use change do not reduce GHGs since protection policies are not executed in forest cover. Moreover, this scenario does not include adopting advanced technologies, better agroforestry practices, or implementing sustainable practices such as organic farming or regenerative agriculture; in this regard, the performance of agricultural activities does not improve. Emissions attributed to changes in land use are equivalent to 4.66 MtCO₂eq in 2015 and would increase to 5.02 MtCO₂eq in 2050, equivalent to an increase of 7.7 %. The total absorption attributed to the change in land use corresponds to 4.21 MtCO₂eq in 2015. In 2050, it is 3.46 MtCO₂eq, representing a decrease of 17.8 %. The growth of forest plantations would increase the absorption of CO₂eq. A total of 0.26 MtCO₂eq for 2015 would increase to 0.33 MtCO₂eq by 2050, equivalent to an increase of 26 %.

In the NDP scenario, emissions generated by changes in land use would decrease by 2050 to a total of 1.19 MtCO₂eq, representing a decrease of 3.47 MtCO₂eq (74 % reduction). For this to happen,

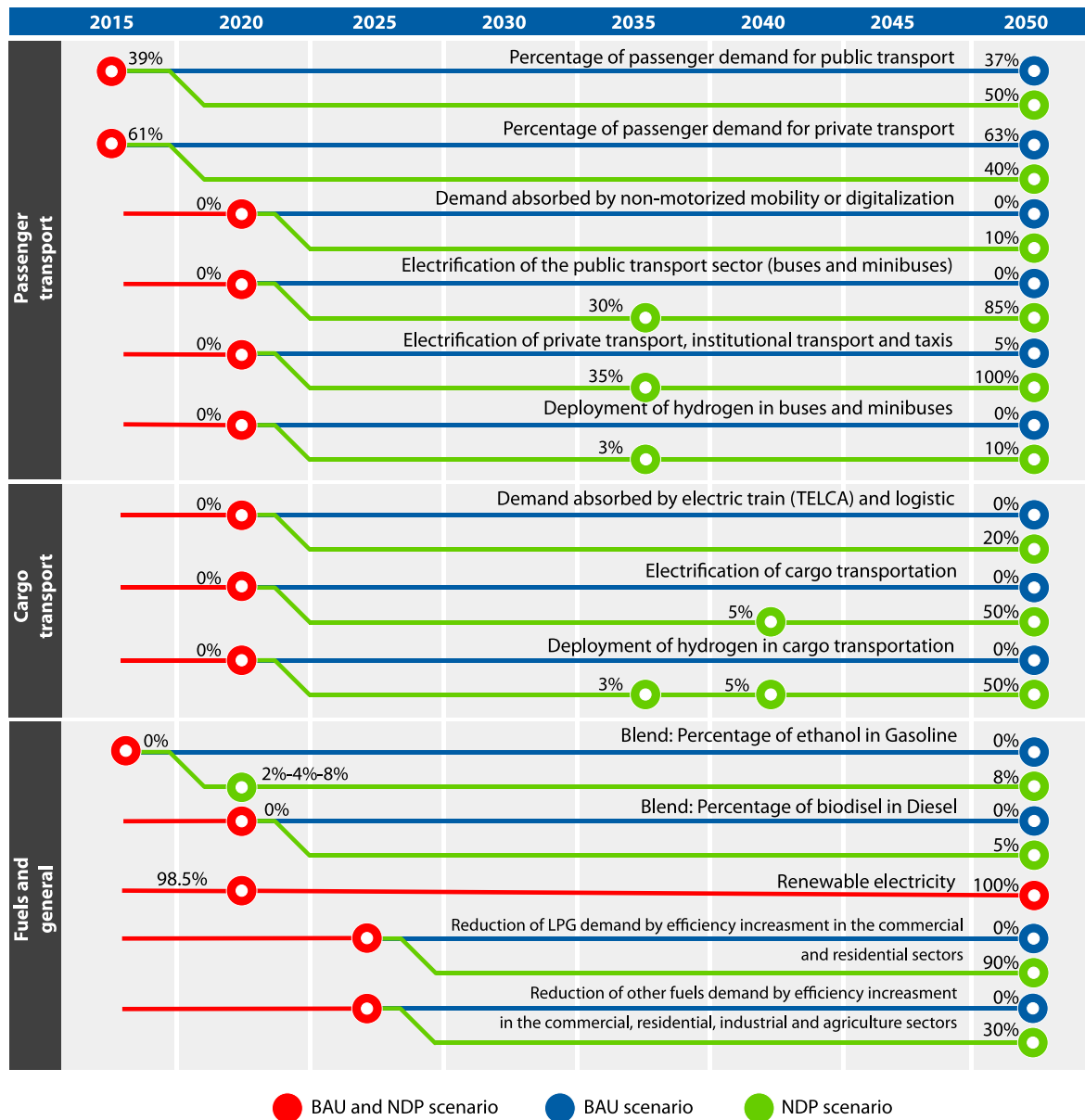


Fig. 4. Synthesis of targets for the NDP scenario in the energy submodel.

legislation and containment measures must be extended to areas not considered in the legislation as "conservation areas," and monitoring must be improved to eradicate illegal mining and logging activities. The critical aspects of this strategy are to preserve the primary forest, increase secondary forest, promote land use change between cropland and grassland, and drive the growth of the sustainable forest plantation industry.

The absorption obtained by the change in land use for 2015 is 4.21 MtCO₂eq, increasing by 17 % by 2050 (reaching 3.48 MtCO₂eq). The increase in secondary forests, pastures, crop coverages, and forest plantations produces the reduction. The primary forest's containment (not loss) is the most significant contribution from 2035. Likewise, absorption from forest plantations would increase by 246 % in the NDP scenario compared to the BAU. The wood from forest plantations or agroforestry systems contributes as a carbon sink since carbon is stored for decades and offsets the emissions produced.

In the BAU, the livestock sector emissions would increase by 33 % due to enteric fermentation, reaching 2.29 MtCO₂eq in 2050. Emissions from crops grow 7.5 %, reaching 0.87 MtCO₂eq. The NDP scenario,

which has an increase in yields, meets the demand requirements with fewer hectares, resulting in land-use GHG reductions of 25 % in livestock and 10 % in crops. Since the NDP considers improved livestock practices (e.g., improving pastures' quality and livestock's feed), emissions are reduced by 50 %. The result of these measures allows reaching emission levels in 2050 of 1.27 MtCO₂eq in livestock and 0.54 MtCO₂eq in crops.

In the BAU scenario, considering liquid waste, a significant delay is reflected in the sanitation issue, in which the current proportion of 14 % of treated wastewater is maintained. Given these conditions, CO₂eq emissions may increase by 56 % by 2050 and reach 1.04 MtCO₂eq. The increase in emissions is boosted by increased discharges without treatment, the stagnation in sanitation coverage, and the use of anaerobic technologies for wastewater treatment. In the NDP scenario, emissions would be reduced by 36.8 %, reaching a total of 0.43 MtonCo₂eq by 2050. The decrease in emissions is due to increased sanitation and wastewater treatment coverage, the replacement of current anaerobic treatment systems with aerobic ones, and proper maintenance of septic tanks.

Fig. 6 shows the costs of the NDP. Achieving decarbonization

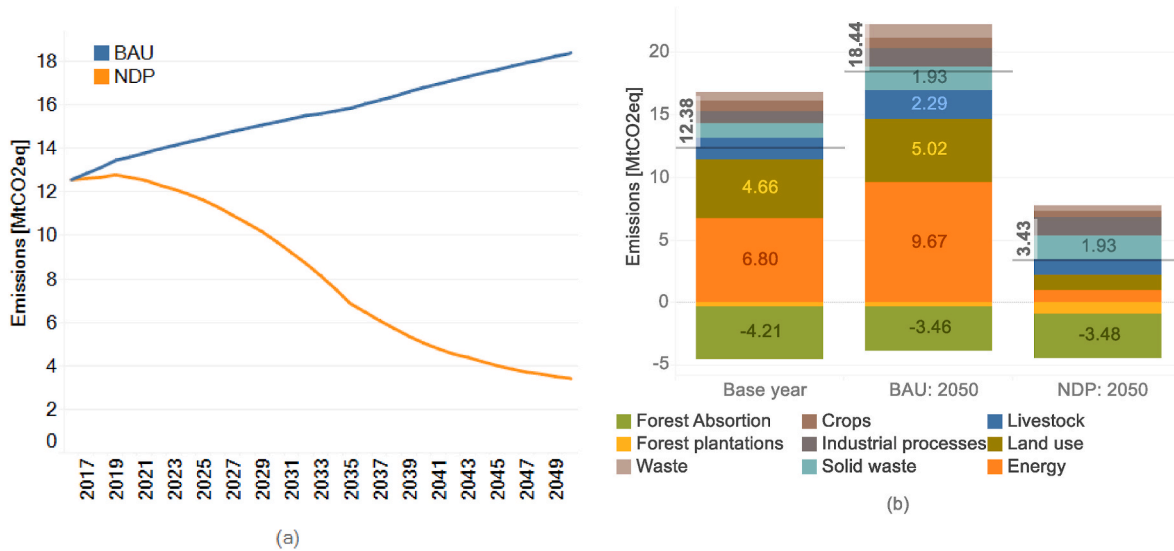


Fig. 5. (a) Total emission trajectories for the BAU and NDP scenarios (b) Total emissions for the base year 2015 and the BAU and NDP scenarios.

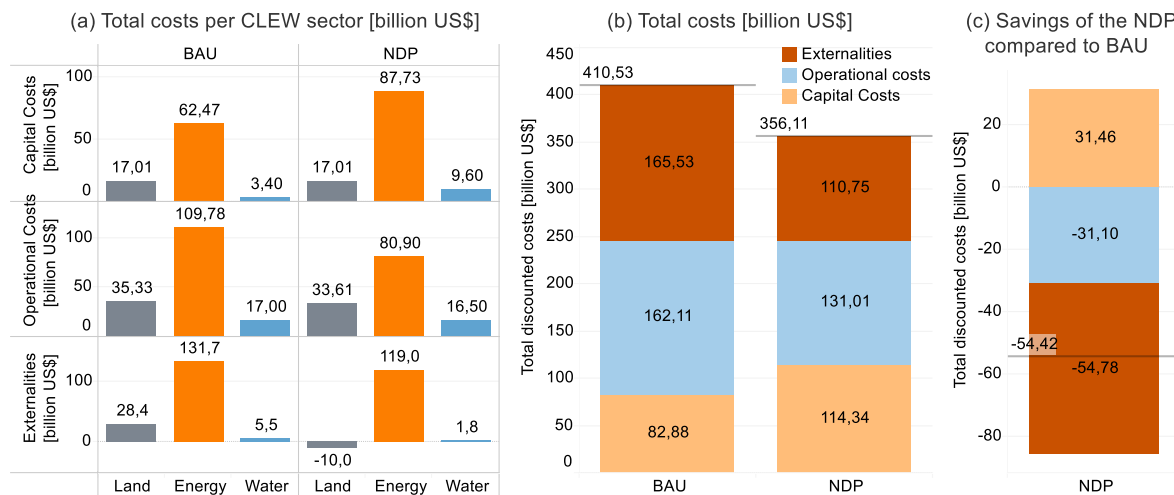


Fig. 6. Socioeconomic metrics from the CLEW-CR model. (a) Total costs per sector. (b) Total aggregate costs. (c) Savings of the NDP compared to the BAU.

requires additional investments up to 2050, estimated at US\$31.46 billion discounted to 2018, considering a 5 % annual discount rate (Fig. 6). The operation of an efficient energy system plus the reduction of operating costs in agriculture and livestock provide cumulative operating savings up to 2050, estimated at US\$ 31.1 billion. The savings in total operating costs almost offset the capital investments, and financially, decarbonization is estimated to bring a total cost to 2050 of US \$356 billion. Considering externalities, the total benefits of the NDP in 2050 are US\$ 54.78 billion (equivalent to savings relative to the BAU). These benefits offset the cost of decarbonization and provide a cumulative net economic benefit to 2050 of US\$54.42 billion, considering an annual discount rate of 5 %.

Fig. 6 shows the cost distribution for each of the analysed sectors. The energy sector, including transportation, requires the most significant investments but simultaneously provides the most considerable savings in operating costs. The decarbonization of the energy and transport sector is highly dependent on technological change, which also requires new infrastructure developments. In the case of the land sector, the costs are moderate since the country already has a large forest cover, and the actions are focused on preservation. The water sector has relatively low costs since the country has extensive infrastructure that allows it to satisfy the demand of a large percentage of the population.

Investments, however, are necessary mainly to guarantee the continuity of the service and reduce non-revenue water. Similarly, concrete projects are proposed for the treatment of discharges and extraction for irrigation that ultimately led to manageable costs for the sector.

The results of our study underline the critical role of robust climate policy and proactive mitigation strategies in the decarbonization process. By comparing the BAU and NDP scenarios, we illustrate the potential for significant greenhouse gas emissions reductions and the necessary investments across various sectors. This comparative analysis showcases the trade-off between short-term financial investment and long-term environmental gains. Our findings resonate with previous research, emphasizing that financial commitments to mitigation strategies can lead to substantial economic and environmental benefits in the long run. The implementation of the technical analysis was possible for the following reasons:

- One of the country's academic institutions (UCR) can conduct analyses like CLEW-based assessments. While sectoral experts have high technical knowledge in their respective fields, CLEW modelers must be able to integrate multisectoral data and knowledge into a computational tool. The modelling teams to carry out such analysis must have diverse skills like technical knowledge in the field of

study, software skills, modelling skills, and communication skills often supported by visualization tools. It is not a requirement that the modelling team is hosted at an academic institution; in other countries, think tanks or specialized research institutes can execute that role.

- The availability of open-source tools like OSeMOSYS that do not require a license fee allows for scaling up the modelling team's size.
- The active leadership and engagement of the DCC allowed a smooth arrangement of stakeholder interactions and a clear vision for the NDC product. Also, the DCC personnel understood the opportunities and limitations of models like CLEW-CR, i.e., they do not define optimal paths that must be recommended without performing a critical assessment of constraints applicable to the model. For this reason, the CLEW CR assessment was sustained in scenario analysis with clearly defined targets explored and consulted with stakeholders.

The process exemplified here could be expanded for an LTS update. However, it would probably have to mobilize more models, especially for the development and economic growth components. For example, OSeMOSYS modelling has been combined with Computable General Equilibrium (GEM) modelling to assess the costs and benefits of the National Decarbonization Plan [55]. Such analyses also must consider long-term uncertainty in the scenarios, requiring the creation of hundreds or thousands of simulations (i.e., model runs) [56].

Other countries in the LAC region can follow this process to update their NDCs or LTSs. For example, by writing this paper's original draft, Ecuador and Guatemala are formulating their LTS with open-source tools. Peru followed a similar approach as Costa Rica to update their Climate Change Strategy [57] and is a case study exemplifying how the process presented here has been applied to more than one country already.

CLEW-CR will allow local researchers and policymakers to explore the costs and benefits of modifying technological supply chains through detailed scenario analysis with an open-source framework. However, more technical work is needed.

6.1. Policy recommendations

The study's findings offer a variety of policy insights for Costa Rica's climate change strategy. The projected reduction in national emissions from 18.4 MtCO₂eq in a business-as-usual scenario to 3.43 MtCO₂eq by 2050 underlines the potential for achieving a decarbonized economy. This ambitious goal, however, requires concerted actions in sectors not fully addressed by the CLEW-CR model, such as industrial processes and solid waste management. It is noteworthy that there are ongoing efforts to create an Industrial Processes model to include this sector in the modelling framework.

The energy sector stands out in the study, where the Nationally Determined Contribution Plan scenario suggests a transformation towards renewable energy sources like solar and wind, combined with a major shift towards transport electrification. This indicates a need for policies that support technological advancements and infrastructure development for electric vehicles and renewable energy. In the land use and agriculture sector, necessary mitigation measures are forest preservation, promoting sustainable land use changes, and the growth of sustainable forest plantations. Thus, policy measures should extend legislation and enhance monitoring to prevent illegal activities impacting forest areas and encourage sustainable agricultural practices.

Waste management also emerges as a critical area, with improvements in sanitation and wastewater treatment projected to reduce emissions significantly. Policies in this sector should focus on expanding wastewater treatment facilities and adopting efficient waste management practices.

From an economic perspective, the study estimates that decarbonization will require investments totalling around US\$31.46 billion by

2050. However, these costs are nearly balanced by operational savings in energy, agriculture, and livestock, coupled with the benefits of accounting for externalities like ecosystem services and health impacts. The cumulative net economic benefit of decarbonization by 2050 is projected to be substantial.

To effectively implement these strategies, comprehensive sector-specific policies based on the study's insights are essential. This includes fostering stakeholder engagement, public-private partnerships, and investing in the necessary infrastructure and technology. Enhancing monitoring and enforcement for forest protection and sustainable land use, alongside financial incentives for sustainable practices, is also crucial.

7. Conclusions

This paper presents a pragmatic approach to developing a CLEW model (CLEW-CR) that combines qualitative and quantitative steps to generate insights for the NDC. The study complements previous efforts and has developed models that allow us to study in detail decarbonization pathways in the land (including agriculture, livestock, and forestry and other land uses) and water sectors. Both are linked with the existing model of the energy and transport sector, thus providing an integrated analysis of a large part of the sectors of the country's economy, except for industrial processes and product use, and solid waste. CLEW-CR is open-sourced (released with this paper) and aspires to be a transparent and accessible tool for further use in the country.

The model's ability to integrate multisectoral data and knowledge has allowed for a comprehensive analysis, providing insights into various sectors. This integration is central to understanding and exploring the interdependencies within the land, energy, and water nexus, which is crucial for effective policymaking and planning. The technical strength of the CLEW-CR model lies in its versatility to explore diverse scenarios and policy options. The participatory process of scenario development, involving stakeholder input and co-creation, has led to the acceptance of emission trajectories and cost metrics, significantly contributing to the robustness of the model's outputs.

This paper provides the approach to assess the costs and benefits of climate mitigation, with the case study of Peru following similar steps [58]. The process presented here can be a reference for other LAC countries that wish to apply open-source and participative approaches to formulate or update their LTS or NDCs. This process is expected to strengthen policy formulation and improve transparency in climate action planning, allowing the country to continue exploring and reporting additional alternatives in an integrated manner to achieve sustainable development with zero net emissions by 2050.

As part of the development of the CLEW-CR model, the work led to the development of two scenarios that illustrate the country's conditions in two possible scenarios. A comparison of the BAU and NDP scenarios shows that emissions could be reduced to 3.43 MtCO₂eq in 2050, representing a reduction of 72 % compared to the base year and 81 % compared to emissions in 2050 in a BAU scenario. The resulting emissions consider successfully implementing the mitigation actions discussed in this study (Figs. 2–4). Thus, achieving total net emissions equal to zero requires efforts in the sectors not captured in the CLEW-CR model.

Achieving decarbonization requires additional investments in 2050 compared to a BAU scenario, estimated at US\$31.46 billion discounted to 2018, considering a 5 % annual discount rate. The operation of an efficient energy system plus the reduction of operating costs in agriculture and livestock provide cumulative operating savings up to 2050, estimated at US\$ 31.1 billion. The savings in total operating costs almost offset the capital investments; overall, the total cost of decarbonization to 2050 is US\$ 356 billion. Including externalities makes it possible to estimate the total accumulated benefits of decarbonization in 2050, corresponding to US\$ 54.78 billion. These benefits offset the financial cost of decarbonization and provide a cumulative net economic benefit

to 2050 of US\$54.42 billion compared to the BAU scenario.

This work serves as a crucial foundation for shaping Costa Rica's NDC 2020, showcasing the technical feasibility of achieving carbon neutrality by 2050 and highlighting the additional societal benefits. The project has established a collaborative framework involving government, civil society, and academia to develop decarbonization strategies. These strategies integrate long-term policies and investments, outlining a sequence of actions towards the targeted goals. The developed conceptual and computational framework will enable Costa Rica to further explore and articulate comprehensive solutions for sustainable development with zero net emissions by 2050.

Future work should assess more technical analysis, particularly for grid expansion and finance. In Ref. [59], the authors explored the relationship between financial variables, electrification levels, types of electricity supply options, and economic benefits, considering a range of uncertain parameters. Moreover, detailing how the industrial sector will decrease emissions or how the strategies can be better aligned with Sustainable Development Goals could benefit policymakers in the future [60].

Credit author statement

Mariana Rodríguez-Arce: Conceptualization, Writing - Original Draft; **Jam Angulo-Paniagua:** Conceptualization, Software, Methodology, Writing - Original Draft; **Luis Victor-Gallardo:** Conceptualization, Software, Writing - Original Draft; **Jessica Roccad:** Conceptualization, Review & Editing, Supervision, Project administration; **Jairo Quirós-Tortós:** Conceptualization, Methodology, Writing - Review & Editing, Supervision, Project administration; **Mark Howells:** Conceptualization, Review & Editing; **Kane Alexander:** Conceptualization, Review & Editing.

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Declaration of competing interest

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

Data availability

All data used is publicly available and the paper includes links

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.esr.2024.101316>.

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