Decarbonising the transport and energy sectors: Technical feasibility and socioeconomic impacts in Costa Rica

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ABSTRACT

Compliance with the Paris Agreement requires the transformation of national economies to meet net-zero carbon dioxide emissions by mid-century. To accomplish this, countries need to define long-term decarbonisation strategies with near- and mid-term actions to determine their ideal future scenario while maximizing socioeconomic benefits. This paper describes the process followed to support the creation of the decarbonisation pathway for the transport and energy sectors presented in Costa Rica’s National Decarbonisation Plan. We discuss in detail the technological pathway of a deep-decarbonisation future that supports reaching net-zero emissions by 2050. Compared to a business-as-usual (BAU) scenario, our results show that the decarbonisation pathway can lead to emissions’ reduction of 87% in the transport and energy sectors by 2050. Energy efficiency, the adoption of electromobility, modal-shift towards public transport and active mobility, as well as reduced demand due to digitalisation and teleworking, are found to be key drivers towards the deep-decarbonisation. These measures combined enable a 25% reduction of primary energy production by 2050. The results highlight that the decarbonisation scenario requires installing 4.4 GW more of renewable power plants by 2050, compared to the BAU scenario (80%). We also show that additional investments for the deep-decarbonisation are compensated with the reduced operating cost. Crucially, we found that the National Decarbonisation Plan results in a lower total discounted cost of about 35% of current Costa Rica’s GDP, indicating that a deep decarbonisation is technically feasible and is coupled to socioeconomic benefits.

1. Introduction

The Paris Agreement establishes a mechanism to fight climate change by contributing to the mitigation of Greenhouse Gases (GHG) emissions [1–3]. For holding global warming well below 2 °C above pre-industrial levels, while pursuing efforts to limit it well below 1.5 °C [4], parties to the Paris Agreement must update their Nationally Determined Contributions (NDCs) in 2020 (and every five years thereafter) demonstrating their progressive commitment towards decarbonisation. Countries are also encouraged to submit their Long-Term decarbonisation Strategies (LTS) to guide this transformation with economic and social goals [5,6].

Costa Rica is one of the few developing countries with absolute and unconditional NDCs compatible with a 2 °C pathway [7,8]. As part of its 2020 updating process, it aims to promote a more ambitious target of net-zero emissions by 2050 while ensuring economic growth and compliance with the Sustainable Development Goals (SDGs). The ambition of the country was ratified in its recently launched National Decarbonisation Plan (NDP) [9], which has been communicated to the United Nations Framework Convention on Climate Change (UNFCCC) as the long-term low-level GHG strategy, in accordance with Article 4 of the Paris Agreement. This initiative demonstrates, once again, the political will of the country to reach net-zero emissions by mid-century.

To produce the NDP, the Government of Costa Rica, led by the Directorate of Climate Change, recognised the need to inform the technological pathway using an innovative approach that combined

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qualitative and quantitative methods [9]. The former was addressed through a stakeholder-driven back-casting participatory approach to establish the policy packages in the ideal decarbonised future and to define the series of strategies and actions (also known as the narratives and storylines) around the decarbonisation pathway. The latter (quantitative analysis) was executed by a local modelling team established at the university using a modelling tool that enabled the understanding of the costs and benefits of this technological pathway in the transport and energy sectors.

The modelling framework used to support the decisions taken in the development of the NDP was produced within the Deep Decarbonisation Pathways Project in Latin America and the Caribbean (DDP-LAC) [2]. It follows the principles of the DDP project [1], and is based on the Open Source Energy Modelling System (OSEMOSYS) tool [10]. It also follows the best practices suggested in Refs. [11] - yet to be fully adopted. The tool considers key details and assumptions informed by the participatory process. Stakeholder involvement and participation supported the assessment of the costs and benefits of deploying zero or low emissions technologies, as well as the identification of measures to promote the use of public transport and active mobility via modal shift from private transport.

This paper describes the innovative approach that combined qualitative and quantitative methods used to produce the decarbonisation pathway for the transport and energy sectors included in the NDP of Costa Rica. We provide a detailed narrative co-created in the stakeholders-driven back-casting participatory process that led to a deep-decarbonisation scenario – a trajectory compatible with net-zero emissions by 2050. We also discuss the collaboration and co-creation process between academia and stakeholders to produce the modelling tool that currently serves in the dialogue of long-term energy policy in the country. We then describe how the narratives were modelled using the OSEMOSYS-CR tool, and present the resulting key technical and socioeconomic outcomes. Overall, this work introduces an analysis framework that is guiding national energy policy. We believe that this effort provides a reliable reference to study the costs and benefits of decarbonisation pathways in other countries, particularly developing countries in Latin America and the Caribbean.

Through comparisons with a business-as-usual (BAU) scenario – one that maps the current trends in the country, our results show that the deep-decarbonisation scenario only requires installing an additional 4.4 GW (80% more) of renewable power plants by 2050. Energy efficiency, the adoption of electromobility, a modal shift towards public transport and active mobility, as well as reduced demand due to digitalisation and teleworking are found to be key drivers towards the deep-decarbonisation and combined they enable a 25% reduction of energy primary production by 2050. In terms of the costs, we found that the deep-decarbonisation scenario requires additional investments (US$ 26.7 billion), which are compensated by lower operational costs (US$ 29.7 billion), bringing a net financial benefit of US$ 2.9 billion to Costa Ricans. If we account for the benefits in terms of health, productivity (due to lower congestion) and fewer accidents due to an electrified transport and a higher use of public transport, our results show that the deep-decarbonisation pathway could bring an economic benefit of around US$ 20.6 billion by 2050. This demonstrates that this deep-decarbonisation is technically feasible and is coupled to socioeconomic benefits.

The remainder of this paper is structured as follows. Section 2 presents an overview of Costa Rica towards the decarbonisation of the transport and energy sectors. Section 3 presents how the narratives of the technological pathway in these two sectors were co-created with stakeholders. Section 4 then assesses technical and socioeconomic outcomes of the analysis carried out as part of the NDP building process. Section 5 discusses other ongoing aspects of the decarbonisation pathway in Costa Rica, and key concluding remarks are finally provided in Section 6.

1.1. The role of Costa Rica in the decarbonisation process

The number of countries that aim to reduce their emissions increased from 20% in 2007 to 76% in 2017 thanks to the Paris Agreement [12]. However, challenges still remain to formulate NDCs compatible with 2 °C and 1.5 °C targets [12]. Existing NDCs “imply a median global warming of 2.6 °C-3.1 °C by 2100” [13]. Moreover, recent studies found that the current policies of the 20 world’s largest economies (G20) are insufficient to achieve their unconditional NDCs, and these countries will need to put in place additional plans [14]. The Intergovernmental Panel on Climate Change (IPCC) has provided substantial information that exposes risks of not achieving GHG emissions reduction not just in terms of disasters or vulnerability, but also offering a reflection on how the trajectories of decarbonisation must be compatible with the achievement of the SDGs [4]. Modelling tools play a fundamental role in providing evidence regarding the implications to decarbonise [15,16]. In energy systems, documentation exists on how models have guided policy decisions to answer different questions, especially in the most industrialized economies using Integrated Assessment Models (IAMs) or a systematic combination of bottom-up modelling tools [1,3,17]. Cost-benefit assessments represent a necessary complement to support policy decisions [18–20].

The Paris Agreement suggests voluntary action. Thus, transparency is essential to evaluate the countries and the global progress in this direction [21]. Countries can make use of the back-casting participatory process to involve the stakeholders, thereby increasing the sense of ownership and legitimacy of decision making processes [22]. It consists of organising workshops with stakeholders that contemplate a series of engagement activities such as creativity methods, regulatory scenarios, evaluations and interactive social learning; to define a realistic vision of a future and the actions that must be developed from the present to achieve it [22–24]. In addition, this type of participatory process can be complemented with other strategies like the Delphi methods, interviews, and surveys to collect criteria from experts, professionals from industry, academia, and government departments [25,26]. In this context, the authors in Ref. [27] present a comprehensive study of how academia can improve the policy-making process.

In Latin-American countries, some efforts provide evaluations of decarbonisation scenarios [28–33]. However, there was a gap in the consolidation of a formal scientific community in terms of modelling capacity (or expertise) and a need to strengthen local capacities. In addition, there is not sufficient information regarding the link between academia or research institutes with the government. To reduce this gap, the DDP-LAC project emerged between 2018 and 2019 [2]. The project involved six different teams (Argentina, Colombia, Costa Rica, Ecuador, Mexico, and Peru) partnered with experts from other countries (Brazil, France, USA, and Sweden). While each team had its own goals, the main purpose of the project was to build capacity and transfer knowledge in model development from one country to another with the ultimate goal of supporting the Latin America country design nationally appropriate decarbonisation strategies. The project benefits from the experiences of the first DDP Project [1], which involved the sixteen countries with the highest GHG emissions in the world conducted between 2014 and 2015. Regional meetings allowed the adaptation of this methodology to the conditions of each participating country, promoted a co-creation process, and enable knowledge sharing between teams.

Costa Rica has an extensive tradition of nature protection and leadership to fight climate change [34]. Its existing policies have resulted in almost 100% renewable electricity [35] and a forest coverage of approximately 60% [36,37]. However, challenges remain in the transport and energy sectors (as in many countries). According to the latest national GHG inventory [38], in 2015, the transport and energy sectors were responsible for 67% of the country’s gross emissions, which were

[1] Numbers may not add due to rounding
analysed using modelling tools (formally discussed in Section 4).

The focus of Costa Rica within the DDPP-LAC was, therefore, to produce an energy systems optimization model (ESOM), widely used for long-term energy planning, that provided insights in terms of the most cost-effective technological transition towards a deep decarbonisation in the transport (in particular) and the energy sectors [39–42]. The Open Source Energy Modelling System (OSeMOSYS) [43,44] was used to build the Costa Rica ESOM. OSeMOSYS which is an open source ESOM framework which has been applied in many studies at different geographic scales and socio-economic contexts [45–48]. The model minimises the total discounted cost (e.g. investment, operation, externalities and any other costs that can be associated to processes within the model) of the system under constraints, considering the level of activities and capacities of processes and commodities [49].

2. Co-creation of the decarbonisation pathway

The process to build the NDP was led by the Directorate of Climate Change using an innovative approach that combined qualitative and quantitative methods [9]. Fig. 1 shows the overall process followed/implemented and its connection to the formulation of climate change policies, which are the result of an agreement between stakeholders. A stakeholders-driven back-casting participatory approach was initially adopted to establish the policy packages in the ideal decarbonised future. This participatory approach also helped defining the narratives around the decarbonisation pathway that were going to be quantitative analysed using modelling tools (formally discussed in Section 4).

2.1. Stakeholder engagement

Bilateral meetings were carried out first between high-level government actors (President, Ministers and Vice-Minister, and Executive Presidents of autonomous institutions), the private sector, civil society, and academia. This not only allowed understanding the different priorities of the sectors and the definition of a national vision, but it also conveyed robustness to the process as key actors were involved from the genesis of the NDP. This generated the base structure of the plan, consisting of ten lines of action, eight cross-cutting strategies, and three times of implementation.

As part of these high-level discussions, two scenarios (and the narratives formally introduced in Section 3.2) were also defined: A Business as Usual (BAU) projecting the current evolution of emissions caused by the growing demand for fossil fuels ignoring the effects of future climate policies; and a deep-decarbonisation scenario that promotes public transport and the electro-mobility consistent with net-zero emissions by 2050 (i.e., the scenario in the NDP) [9].

The engagement with key actors also helped define sectoral trajectories for the BAU scenario. The participation of each sector also helped to define 2050 targets for the decarbonisation pathway. Fig. 2 summarizes the main outcome of this first consultation process in which key actors shape the NDP.

2.2. Scenario building: storylines for decarbonised the transport and energy sectors

Two series of workshops with directors, sectoral and key technical experts were then carried out aiming to build the decarbonisation scenario and narratives according to the view of experts from the different lines of action. 154 and 192 participants were involved in each workshop. They support defining some aspects for both the BAU and the decarbonisation scenario in the transport and energy sectors (the focus of this paper).

In terms of the narratives for the BAU scenario, the narrative considers that energy consumption (including that from transport), the gross domestic product (GDP), population growth, and aspects related to the transport sector (e.g. occupancy rate, vehicle fleet growth, and annual average distance) will follow a trend based on historical data. For the construction of new power plants and transmission lines, it uses as reference the expansion plans from the system operator that suggest a long-term renewable and power system stability [50]. Following international trends of technological development and innovation, the scenario considers a moderate penetration of distributed generation (5% of total capacity), especially rooftop photovoltaic systems; and a conservative deployment of light-duty electric vehicles and electric buses (5% penetration by 2050 in both fleets), as well as small costs reduction in technologies.

In terms of the narratives for the deep-decarbonisation scenario (i.e., the NDP), we consider that the social and economic situation described in the BAU scenario remains the same. According to policies described in Section 2, the three main activities towards a deep decarbonisation of the transport and energy sectors are: i) urban change and non-motorized mobility; ii) the replacement of fossil fuel technologies; and, iii) the switch of carbon-intensive energy carriers to zero- or low-emissions technologies. For all these initiatives, the scenario assumes that the Government will develop the necessary mechanisms to finance projects, promote a behavioural change in society, and generate an effective and transparent communication. The storylines for each of the above activities are described below:

• Urban planning and mobility: The scenario considers the on-going efforts to implement a mass rapid transport system with an Electric Passenger Train system implemented in two phases as a backbone, integrated with a modern public transport scheme organised by sectors. This activity will be complemented with best urban planning practices, including vertical construction, the concentration of commerce and services, the incorporation of bike lanes, and the integration of environmental elements, which help densify the city in terms of population, promoting walkability and sustainability. All these initiatives could greatly contribute to the reduction of light-duty vehicles and a higher use of public transport (modal shift). In addition, measures aiming to promote teleworking, or the digitalisation of businesses will reduce energy consumption and improve the efficiency of the systems.

• Switching fossil fuel technologies: The scenario considers energy sustainability with low levels of emissions as a fundamental axis of a long-term policy. It is expected that the market conditions will be adequate and additional incentives will be promoted for the import
and purchase of electric vehicles, not only for private use, but also in buses and cargo. In addition, the deployment of the Limón’s Electric Cargo Train that will work with a load transfer centre for the main cargo route in the country is included as a promising measure to reduce carbon emissions from heavy freight. Finally, the country will consolidate flexibility, intelligence, and resilience of the electric system under the concept of smart grids. The details of the modelling process of this switching is discussed in Table 1 within Section 4.1.

- **Switching energy carriers**: This action directly affects the entire fossil fuel-based system, but it has a greater impact on the cargo transport sector. First, it consists of using a blend of fossil fuels with biofuels, substituting in this way an import for a locally produced fuel at the competitive market price. Furthermore, the scenario also considers the incorporation of hydrogen, particularly for heavy duty vehicles (cargo and buses) and liquefied petroleum gas (LPG) as a transition fuel. It is assumed that hydrogen is available by 2030. The details of the modelling process of this switching is discussed in Table 1 within Section 4.1.

Fig. 3 summarises the targets for each scenario (BAU and NDP) according to the main storylines and ambition set by the stakeholders. It must be noted that some targets are applicable for both scenarios, thus they are marked as BAU&NDP. The decarbonisation scenario implies modal shifts and reductions in distance travelled promoted by compact cities. It involves a transition to public transport that increases to 50% of motorized kilometres travelled by 2050 compared to often significantly lower figures (down to 40%) in the BAU scenario. This consequently implies a reduction in the demand of passenger kilometres in the private transport (from 61% in 2015 to 40% in 2050). The NDP envisions that, by 2050, public transport should cater for most of the demand in metropolitan areas, and that non-motorized modes (including walking and cycling and reduced demand due to the digitalisation of jobs and teleworking) should increase their contribution to 10% of mobility by 2050. The deep-decarbonisation also implies a technological pathway to zero or low emissions technologies reaching 85 and 100% in the public and private, institutional and taxis fleet. Hydrogen-based buses and minibuses are also part of this technological pathway to net-zero emissions reaching a 10% of penetration by mid-century. This pathway also involves a transformation in the freight sector including battery- and hydrogen-based technologies. Under based considerations, a 50/50 shared is considered by 2050. Biofuels also play an important role in the emissions reduction, along with reduced used of LPG in the commercial and residential sectors. Finally, we consider that the electricity mix will be 100% renewable.

3. Assessment of decarbonisation pathways

Once the qualitative activities were concluded, a quantitative assessment of the decarbonisation pathway was carried out. This involved the use of modelling tools to assess the most cost-effective technological pathways while also studying the corresponding socioeconomic effects.

3.1. The OSeMOSYS-CR model

As part of the DDP-LAC Project [2], Costa Rica, via the University of Costa Rica and international experts from the KTH - Royal Institute of Technology (Sweden), developed OSeMOSYS-CR. The energy system model is maintained by academia, ensuring that it is updated with the latest available information. While building the model key institutions in the transport and energy sectors were involved in capturing the respective particularities. They also provided data that currently feeds the technological and socioeconomic assessments. Other sources of data were international databases and the TIMES-CR model [51] that was previously built for the country by external modelers.

The OSeMOSYS-CR was built on a countrywide scale including the entire process of energy transformation from primary energy supply to demands and considering the effect of rainy and dry months. In terms of commodities, the model contains a set of renewable sources to produce electric power systems, transport sector, and infrastructure. The model combines more than one hundred commodities and two hundred technologies. OSeMOSYS-CR was recently extended, as part of other ongoing efforts in the country to estimate the costs and benefits in terms of health, congestion, and the number of accidents. Fig. 4 presents a simplified representation of the reference energy system of the OSeMOSYS-CR model. It is structured in terms of primary sources, main transformation processes and final demands. Table 1 finally details the process of incorporating the strategies in OSeMOSYS-CR while describing parameters, values, functions, and specific considerations involved.
Summary of parameters and actions in OSeMOSYS-CR model to represent the deep-decarbonisation strategy.

<table>
<thead>
<tr>
<th>Subsector</th>
<th>Action</th>
<th>Description on modelling process</th>
</tr>
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<tbody>
<tr>
<td>Passenger Transport</td>
<td>Mode shift: Demand in public and private sector</td>
<td>Mobility demand is an input to the model. We use an S-curve to model a smooth transition from private to public transport with a target by 2050. Load factors, distances, and efficiencies are similar to BAU. To estimate the costs of this process, we use coefficients linked to the level of activity and based on the urban planning studies developed in Costa Rica.</td>
</tr>
<tr>
<td>Cargo Transport</td>
<td>Demand absorbed by the Limon’s Electric Cargo Train and Logistic</td>
<td>The transition is carried out by reduction of the demand in private and public transport from 2022 to 2050 following a logistic function. The cost of the infrastructure was embedded with the mode shift. In terms of the digitalisation, we do not consider cost due to the existing and growth communication infrastructure of the country. Similar to the mode shift, we use an S-curve to model the adoption rate of technologies. We parametrized the curve considering targets by 2030, 2035, and 2050. The procedure consists of introducing a level of activities for low-carbon technologies while the proportions of groups of technologies are kept proportional to the base year. The Limon’s Electric Cargo Train begins to absorb demand for heavy freight linearly from 2022 to 2024, in which the electric train reaches a maximum value of 10% through 2050. The logistic actions reduce the light freight demand, and we use the same procedure as Limon’s Electric Cargo Train, but with 2022 and 2030 as transition years. In both cases, the capital cost is introduced linearly in the transition years. Fixed costs also increase in the transition period to the maximum rate, which remains until 2050.</td>
</tr>
<tr>
<td>Fuels and general</td>
<td>Blend with biofuels</td>
<td>A specific process in the model makes the volumetric mixture of biofuels and fossil fuels, defining percentages of activities. For these cases, it establishes a linear level of activity from 0 to 8% for ethanol and 0–5% for biodiesel, between 2022 and 2050. This consideration responds to the uncertainty linked to biofuel imports and productions. At this time, we consider only importations and comparable prices with fossil fuels.</td>
</tr>
<tr>
<td>Renewable electricity</td>
<td></td>
<td>The assumption limits the operation of thermal power plants (maximum operation) from 2.5% to 0% between 2022 and 2050.</td>
</tr>
<tr>
<td>Efficiency</td>
<td></td>
<td>It is assumed a linear demand reduction of 0% to 10% between 2022 and 2050 as a response to the increased efficiency in the energy sector.</td>
</tr>
</tbody>
</table>

OSeMOSYS-CR also includes estimation of externalities associated with: i) pollution from fuel consumption, ii) accidents related to vehicle use, and iii) cost of vehicle congestion. These were selected based on their relevance to the country and data availability. Other externalities could be added according to stakeholder needs. The estimation related to pollution is based on the work in Ref. [52]. Here, the authors provide an external cost in dollars of local air quality for Costa Rica per litre of fuel consumed. These factors depend on estimated mortality rates based on: pollution ingested, mortality rates for strokes, obstructive pulmonary disease, ischemic heart disease and lung cancer, among others. Regarding accidentally, the model uses a factor per passenger that can be obtained from historical data if available. The work in Ref. [52] also provides information about accidentality, but it comes in dollars per litre; thus, assumptions will need to be made to be used in energy and transport models. OSeMOSYS-CR uses estimations made in the country and reported in Ref. [53]. These costs include medical costs, vehicle destruction, and lost productivity. Those costs combined with information from [54] about accident statistics allow defining a coefficient in dollars per passenger-kilometre. Finally, for congestion, the parameters in OSeMOSYS-CR are based on [53] which includes costs per vehicle that capture the cost of the lost productivity, higher maintenance of vehicles and stress. Full description and the underlying data of the OSeMOSYS-CR can be retrieved from the online documentation [55] and the model is available under an open-source license repository [56].

3.2. Technological assessment

The emissions trajectories shown in Fig. 5 (left side) indicate that the decarbonisation scenario brings a total annual reduction of 8.4 MtCO2e by 2050, representing 13% of the emissions in the BAU scenario for the same year. Reducing emissions while ensuring that demands are satisfied then led to a much lower carbon intensity (right side). This occurs primarily due to the electrification of the transport sector and the shifting towards public transport. These two strategies have the potential not only to reduce emissions, but also to lower energy consumption due to higher efficiencies.

The technological transition presented for the public and private transport sectors in Fig. 6 (left side) shows the underlying consideration in the use of public transport and the electrification process that takes places in the different passenger demands. It highlights that electromobility in the private sector (e.g., sedans, SUVs, etc.) starts to grow by 2022 as the technology is already accessible for many people. While the deployment of electric buses starts from 2021, a massive adoption takes place primarily after 2030 – when the technology becomes even more cost-effective.

The right side of Fig. 6 depicts the technological transition expected for the cargo transport. Demand starts to be satisfied from 2021 using the cargo train, described before as the Limon’s Electric Cargo Train, and the use of this train grows linearly until reaching 10% of the total demand by 2050. The decarbonisation process in the cargo sector is then complemented by the electrification of trucks and mini trucks. The deployments, however, intensifies after 2030 accounting for the availability of technologies. The electrification of the trucks and mini trucks is expected to reach an 85% by 2050. 95% of the total demand by 2050 is expected to be satisfied using zero-emissions technologies.

To maximize the technical benefits of electrifying the transport sector, a renewable energy supply must be adopted. Fig. 7 highlights that the decarbonisation scenario reduces the use of fossil fuels and introduces new wind and solar energy capacity (mainly for electricity production). Since Costa Rica imports 100% of its fossil fuels, reducing these imports will lead to savings as a result of lowering the oil expenses. However, it is likely to affect the fiscal revenue of the Ministry of Finance as the fiscal structure is highly dependent on the transport sector [5].

Increasing the penetration of renewables, which are expected to become more cost-effective with time, is likely to bring benefits in terms of electricity tariff as the existing mechanism to define the tariff considers the investments made by power utilities. Thus, while the deep-decarbonisation scenario may seem ambitious, its realization requires deploying technologies that are already available in the market with a lower cost than fossil-intensive ones. These results show that energy efficiency, the adoption of electro-mobility, modal shift towards public

The Limon’s Electric Cargo Train is under development to transport goods from the Caribbean side of the country to the north where freight hubs are planned [63].
transport and active mobility, as well as reduced demand due to digitalisation and teleworking, are found to be key enablers towards the deep-decarbonisation and they combined can allow reaching a 25% reduction of energy supply by 2050.

New renewable power plants will support the electrification of the transport sector. The existing Expansion Plan of the Generation 2018–2034 [50] accounts for the growing existing demand, currently growing 2% on average annually growth. The electrification of the transport sector, however, may require additional plants. Compared to the BAU scenario in 2050, the study found that a deep-decarbonisation requires about 4.4 GW of additional installed capacity (Fig. 8), being solar and wind the main technologies due to their decreasing total cost compared to other technologies. Their operation is, nonetheless, needed primarily after 2035 given that the massive deployment of electro-mobility starts to take place. This implies that investments may not be significant as the cost of low carbon generation technologies are expected to be much lower in the future [5, 57].

3.3. Socioeconomic assessment

From a financial perspective, the decarbonisation process requires capital investments that are compensated with reduced operational costs. Deploying zero or low emission technologies may lead to higher investment costs, but their operation typically leads to savings. In addition, the costs of zero carbon technologies are dropping rapidly whereas business as usual is becoming more expensive and exposed to transition risks including asset stranding. The cost of batteries for electric vehicles has also seen a six-fold reduction in just eight years, which is expected to continue. Fig. 9(a) (b) indicate that the deep-decarbonisation scenario requires additional investments of US$ 26.7 billion by 2050 that are contrasted with savings of US$ 29.7 billion by the same period, thus leading to a positive net financial benefit of US$ 2.9 billion (approximately 5% of current Costa Rica’s GDP).

Additional benefits can surpass investments. Decarbonising the transport sector brings opportunities to improve mobility, reduce local air pollution, and improve the quality of life. Time lost in congestion and the cost of accidents is also an expensive problem. In our analysis, we estimated costs of time lost due to congestion, accidents, and the health impacts of local air pollution. Moving to efficient public transport systems and to electro-mobility could be one of the greatest opportunities to support the transition to net-zero emissions while bringing substantial benefits to the economy and society. An effective urban transport system based on electric buses can cut congestion, accidents and local pollution while taking advantage of renewable electricity and saving money. The analysis of the deep-decarbonisation highlights that accounting for these externalities can increase the economic benefits of decarbonising the transport and energy sectors to about US$ 20.6 billion [Fig. 9(c)], which represents almost 35% of current GDP.

The timeline of these socioeconomic benefits (Fig. 10) indicates that investments surpass savings in the short-term (2020–2030). The
investments are related mainly to the initial roll-out of electric vehicles in the private fleet, the electrification of light freight transport, the first phase of the passenger train deployment, and new renewable power plants. While investments are still needed in the mid and long-term, operational savings (highly related to lower fossil fuel consumption) always compensate capital costs; thus, bringing net financial benefits. In these two periods, the investments in low carbon freight trucks are predominant. Furthermore, it includes the second phase of the electric passenger train and the transition to more efficient public transport, while continuing the electrification of buses and private vehicles. In the energy sector, renewable energy infrastructure continues to support the technological transition. If we add up the benefits in terms of health, congestion, and accidents, the socioeconomic benefits in the mid and long terms represent almost 13 and 26% of current Costa Rica’s GDP; thus highlighting that benefits are greater as the mid-century goal is reached.

4. Discussion

Costa Rica’s NDP represents its long-term, low-level GHG strategy to achieve net-zero emissions by mid-century under the Paris Agreement (Art 4). This plan is one of the first to trace a road map towards the decarbonisation, including a coherent vision, stages of development, policy packages, and enablers that give it an international relevance. This paper has described how Costa Rica analysed the plan’s energy and transport-related climate change policy objectives. Exploring and analysing GHG emission trajectories provided support to understand the transition in these sectors while at the same time building local capacities to answer policy questions. In this context, our work represents the first systematic study to evaluate decarbonisation pathways in Costa Rica. Besides, installing these capacities in the local academy brings as an added value, the concept of transparency, maintainability, and innovation.

Furthermore, the NDP’s stakeholder engagement ensured the inclusion of all perspectives from relevant actors in decarbonisation pathways. This process also served to introduce the concept of transformational change and the strengthening of the concept of co-creation in the country. The participatory process also contributed to establishing a permanent network of actors, defining each participant’s roles and responsibilities. As a result, the general methodology and the evaluation process using OSeMOSYS-CR gained national acceptance and credibility. The analysis done using the OSeMOSYS-CR has led to updating process of the National Energy Plan, which includes aspects from the transport sector, and there are current efforts to assess the techno-economics of this Plan.

The OSeMOSYS-CR model was designed following a bottom up approach capturing capital and operational costs for the different sources.
technologies deployed in the model. It also quantifies external costs linked to air pollution mortality, congestion, and accidents. Through scenario comparison, it can be used to estimate the net cost or benefit of different strategies. Thus, it could also be used to assess the costs and benefits of specific projects such as those associated with the implementation of the electric train in Costa Rica or the construction of power plants.

The challenges posed by energy optimizations models and their limitations, however, must be recognised to truly inform policy makers. While the analysis allows understanding the benefits of investing in transport infrastructure, it does not specify where those investments should be made. It allows concluding on the benefits of modal shift; however, additional instruments are needed to enable the modal shift towards public transport and sustainable mobility. In terms of the challenges in the electricity sector, the analysis of power system requires special attention, not just in technical aspects such as stability, security, reliability, and optimal operation of power grids but in the investment of the energy system, energy markets, regulation, and social impacts (tariffs). With the growth of the smart grid concept, there is still a need to study how demand side management could benefit the decarbonisation process.

The assessment performed here for the transport and energy sectors captures the most plausible decarbonisation pathway for Costa Rica.
discussed with stakeholders. Inherent uncertainties related to techno-
technological costs, demands, efficiencies, availability of technologies, among
others, need to be investigated to evaluate their effects in the technical
viability and socioeconomic impacts. To capture these effects, the cost
and benefits of implementing the actions described in the NDP have
been analysed applying a Robust Decision Making methodology [58,
59].

Our results showed that this process would lead to a significant
reduction of fossil fuels imports. Since government income from the
transport sector represents about 20% of the total revenue in the
country, the electrification will reduce revenues from gasoline and
diesel taxes. Therefore, it is necessary to anticipate these changes to
allow for alternative fiscal measures to be planned and implemented. To
manage the potential impacts, the NDP can be used to progressively
adjust the rate of taxes on gasoline, electricity and vehicle ownership
and operation based on the mid-century targets. Consequently, efforts
are necessary to study fiscal options to compensate the fiscal impact that
may result from the decarbonisation of the transport sector.

Finally, while OSeMOSYS-CR allowed studying decarbonisation
pathway for the transport and energy sectors, we need to provide the
same scientific approach to the other lines of action of the NDP related to
agriculture, land use, and land use change. The last three sectors can be
integrated with the OSeMOSYS-CR through the Nexus concept to reach a
complete integrated Climate-Land-Energy-Water systems model
(CLEWs) [60–62]. On-going efforts have been developed by the authors
as part of the academic contributions for the Costa Rican NDC’s
updating process, which include the production of a modelling frame-
work to integrate the energy, land and water sectors (LEW) and the
assessing policy scenarios compatible with the net-zero emission.

Fig. 9. Cost comparison by scenario: (a) Capital and operational costs, (b) Financial benefits, (c) Socioeconomic benefits. Values are discounted at 5% up to 2050.
Note: Numbers may not add due to rounding.

Fig. 10. Timelines of socioeconomic benefits. Values are discounted at 5% up
to 2050.
Note: Numbers may not add due to rounding.
5. Conclusions

This paper has described the innovative approach that combined qualitative and quantitative methods used to investigate a deep-decarbonisation pathway for the transport and energy sectors of Costa Rica, in line with the that is National Decarbonisation Plan. We discussed in detail the technological pathways of a deep-decarbonisation future that assists the country reaching net-zero emissions by 2050. We have detailed a narrative co-created in the stakeholders-driven back-casting participatory process that led to our deep-decarbonisation scenario – a trajectory compatible with net-zero emissions by 2050. We also discussed how academia engaged with stakeholders to produce the modelling tool that currently serves in the dialogue of long-term energy policy in the country. We showed how the narratives were modelled using the OSeMOSYS-CR, and key technical and socioeconomic outcomes resulting from the deployment of the narratives within the model. Overall, this work introduced an analysis framework that is guiding national energy policy and we believe that this effort provided a reliable reference to study the cost and benefits of decarbonisation pathways in other countries, particularly developing countries in Latin America and the Caribbean.

Compared to a business-asusual (BAU) scenario, our results show that the decarbonisation leads to a reduction of 87% of the emissions from these sectors by 2050. The reduction happens primarily as a consequence of an intensive electrification of the transport sector in its private, public, and freight fleets. Energy efficiency, modal shift towards public transport and active mobility, as well as reduced demand due to digitalisation and teleworking are found to also be key drivers towards the deep-decarbonisation. All this is complemented with an electricity mix that is kept renewable and ensures that the electrification of activities occurs with almost zero emissions from the electricity sector.

The decarbonisation of the transport and energy sector also showed a reduction of 25% in energy supply by 2050 which in turn leads to a carbon intensity four times smaller than the BAU scenario. The results have also highlighted that the decarbonisation scenario requires installing only 4.4 GW more (80%) of renewable power plants by 2050. In terms of the costs, we found that the most ambitious scenario requires additional investments (US$ 26.7 billion) which are compensated by lower operational cost (US$ 29.7 billion); thus, leading to a positive net financial benefit to Costa Ricans. If we account for the benefits in terms of health, productivity (due to lower congestion) and accidents, our results show that the National Decarbonisation Plan compatible with net-zero emissions by mid-century could bring an economic benefit of around US$ 20.6 billion by 2050 (about 35% of current national GDP); thus, demonstration that a deep-decarbonisation is technically feasible and can incur also in socioeconomic benefits.

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References


