Journal of Cleaner Production 379 (2022) 134781

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Identifying cross-sectoral policy synergies for decarbonization: Towards short-lived climate pollutant mitigation action in Costa Rica

Luis Victor-Gallardo [a], Jessica Roccard [b], Patricia Campos [c], Christopher S. Malley [d], Elsa N. Lefevre [e], Jairo Quiros-Tortos [a,*]

[a] School of Electrical Engineering, University of Costa Rica, San Jose, 11501-2060, Costa Rica
[b] Development Observatory Research Center, University of Costa Rica, Costa Rica
[c] Directorate of Climate Change, Costa Rica
[d] Stockholm Environment Institute, Department of Environment and Geography, University of York, United Kingdom
[e] United Nations Environment Programme, Paris, France

ARTICLE INFO

Handling Editor: Jian Zuo

Keywords:
Sustainable development
Planning instrument
Decarbonization
Value chain analysis
Costa Rica

ABSTRACT

Decarbonization is a process that transforms economies to lower greenhouse gas (GHG) emissions per unit of economic output, aiming towards net-zero GHG emissions. This process could also reduce short-lived climate pollutant (SLCP) emissions, including black carbon and methane. They have relatively short atmospheric lifetimes but have large radiative forcing and impact human health. Therefore, reducing SLCPs can improve air pollution and help mitigate climate change. Costa Rica was one of the first countries to have a decarbonization plan, and many others have stated their goal to reach net-zero emissions by around mid-century. However, reducing SLCP emissions as an economy decarbonizes is not guaranteed, and few examples in the literature have assessed how decarbonization impacts SLCPs. This paper estimates the SLCP emission reductions from Costa Rica's decarbonization plan. Through a value chain analysis and the identification of implementation barriers, the paper also evaluates which policy instruments can advance SLCP mitigation in multiple sectors, creating implementation synergy. We find that mitigation measures, by 2050, in the transport, agricultural, solid waste, and industrial sectors avoid 25.2 kt of black carbon emissions (23 times the 2018 emissions) and 2167 kt of methane (15 times the 2018 emissions). However, the country faces financial and governance challenges in each sector that will need overcoming to implement the intended mitigation measures. We identify a comprehensive environmental tax reform, the overhauling of urban regulatory plans, the strengthening of institutional capabilities, and low-carbon investment with favorable financing as crucial cross-sectoral policy synergies that will advance the implementation of SLCP mitigation.

1. Introduction

The increased ambition in recent years to meet the Paris Agreement goals and decarbonize the world's economy has increased the pressure to implement mitigation measures that reduce greenhouse gas (GHG) emissions (Ou et al., 2021). While current climate policy ambition and implementation levels are inconsistent with science-based emission reduction pathways (UNFCC, 2021), there is growing evidence that decarbonization will produce economic benefits (Benavides et al., 2021; Godínez-Zamora et al., 2020; Groves et al., 2020; Quirós-Tortós et al., 2021). Such benefits are associated with higher efficiency and avoided fuel costs and externalities, surpassing upfront financial costs of new technology and infrastructure. Decarbonizing can also contribute to achieving multiple Sustainable Development Goals (SDGs) (Haines et al., 2017) and creating jobs (Saget et al., 2020). However, achieving the desired results requires articulating a social and political consensus to design and implement short-term actions consistent with long-term decarbonization (Bataille et al., 2016).

In this context, some anthropogenic activities that produce GHG emissions also co-emit short-lived climate pollutants (SLCPs). SLCPs are a collection of pollutants, including black carbon, methane, tropospheric ozone, and hydrofluorocarbons (HFCs). They have positive radiative forcing and relatively short atmospheric lifetimes (from days to around 15 years) compared to long-lived GHGs like carbon dioxide (CO_2) and nitrous oxide. Here we focus on black carbon and methane:

* Corresponding author.
E-mail address: jairohumberto.quiros@ucr.ac.cr (J. Quiros-Tortos).

https://doi.org/10.1016/j.jclepro.2022.134781
Received 23 April 2022; Received in revised form 29 September 2022; Accepted 17 October 2022
Available online 22 October 2022
0959-6526/© 2022 Published by Elsevier Ltd.

Abbreviations

GHG	Greenhouse gas
SLCPs	short-lived climate pollutants
HFCs	hydrofluorocarbons
CO_2	carbon dioxide
NDP	National Decarbonization Plan
AFOLU	agriculture, forestry, and land use
NDC	Nationally Determined Contribution
OSeMOSYS	Open-Source Energy Modeling System
CLEW	Climate Land Energy and Water

- Black carbon emissions originate from incomplete fuel combustion. It lives days in the atmosphere and could have a higher warming impact than CO_2 (Climate and clean air coalition, n.d.-a). Black carbon is a component of particulate matter (PM2.5), the air pollutant most associated with negative health effects through cardio-respiratory diseases (World Health Organization, 2021).
- Methane has an atmospheric lifetime of approximately 12 years and warms the planet 86 times more than CO_2 over a 20-year period (Climate and clean air coalition, n.d.-b). It has contributed approximately 0.5 °C of global temperature increases since pre-industrial times (IPCC, 2021). Reducing methane from the three major anthropogenic sources (fossil fuel production, agriculture -livestock and rice production- and waste) would reduce the rate of global warming in the near term and is a necessary complement to large-scale reductions in carbon dioxide emissions to limit the global temperature increase to 1.5° (IPCC, 2018; Roe et al., 2019). Methane also contributes to the formation of tropospheric ozone, an air pollutant that causes respiratory diseases (Malley et al., 2017).

Some countries have explicitly identified, evaluated, and prioritized mitigation measures that reduce black carbon and methane to simultaneously improve air quality and human health and slow the rate of global warming in the near term (Klausbruckner et al., 2016). However, climate change and air quality management are often treated separately in legislation and policy-making, e.g., in South Africa (Klausbruckner et al., 2016) and the European Union (Workman et al., 2019). In Costa Rica, a country of five million people in Central America, the National Decarbonization Plan (NDP) (Government of Costa Rica, 2019) is the country's pathway to achieving net-zero GHG emissions by 2050, often referred to as a long-term strategy (IDB; DDPLAC, 2019). It outlines short and long-term sector-specific actions to advance GHG reductions and economic prosperity simultaneously.

While the NDP does not explicitly cover SLCPs and air pollution mitigation alongside GHG reductions, many of the actions outlined within the NDP could simultaneously reduce SLCPs. An initial step to harmonizing climate change mitigation and air quality goals is to develop an integrated GHG and SLCP emission inventory. Costa Rica included an integrated inventory in its Third National Communication (Instituto Meteorológico Nacional, 2019) and included black carbon emission reduction targets in its Nationally Determined Contribution, as well as including methane within the scope of its GHG reduction targets (Government of Costa Rica, 2020). Other countries, such as Nigeria (Malley et al., 2021) and Chile (Center for Climate and Resilience Research, 2020), have developed specific SLCP mitigation plans.

Documents such as long-term strategies or specific SLCP mitigation plans outline mitigation measures with policy objectives. For example, the NDP has the *policy objective* of reaching a 95% zero-emissions private transport fleet by 2050 -the "what" a policy is aiming to achieve according to (Bouma et al., 2019)-. The mitigation measure is the *electrification of the vehicle fleet,* and according to the NDP, favorable fiscal and financial incentives can be *policy instruments* that implement the measure and reach the objective -the "how" the policy objective is achieved-. A mitigation measure can have multiple and different policy objectives, e.g., a different target or specific targets for specific sectors. Moreover, multiple policy instruments can advance the implementation of the measure.

Using these three concepts to assess the NDP, assessing its mitigation measures can provide policymakers with information about the extent to which SLCP emissions can decrease under the current climate mitigation ambition. Policymakers should also assess implementation impacts and barriers (UNEP & CCAC, 2016), e.g., economic costs, organizational inertia, and long-term political uncertainty (Meyer, 2020; Workman et al., 2019). Doing so can inform what combinations of policy instruments advance action through synergy, i.e., instrument interactions that reduce emissions more than their individual effects (Mainali et al., 2018).

Mixing policy instruments addresses market, governance, or behavioral barriers to objectives (Bouma et al., 2019), e.g., a combination of performance and technical standards, carbon pricing, adoption subsidies, innovation support, and information provision (van den Bergh et al., 2021). Hence, policymakers can prioritize instruments that advance multiple SLCP mitigation measures in multiple sectors. Synergies facilitate harmonizing national policies, limit the complexity of climate policy packages (van den Bergh et al., 2021), integrate policy domains and jurisdictions (Medina Hidalgo et al., 2021), and avoid policy combinations that increase costs and resource competition (Akinyi et al., 2021).

Long-term strategies may recommend new emission standards, carbon pricing, adoption subsidies for existing efficient technology, innovation support through R&D subsidies, information provision or technological transfers, direct investments, fiscal incentives, and government procurement (Pang et al., 2020; Thacker et al., 2019). Whether these instruments become enforceable depends on their barriers (e.g., political), the availability of financial resources (Battiston et al., 2021), and the roles national governments, non-state, and sub-national authorities play in managing implementation (Hsu et al., 2019). Some studies assess barriers to implementing technological transformations in cities (Mosannenzadeh et al., 2017) or organizations (Wang et al., 2020). However, to the best of the authors' knowledge, there is a gap in the literature with practical integrated quantitative analyses for economy-wide decarbonization strategies and identification of instrument synergies that advance multiple measures considering SLCP mitigation. The novelty of this paper is addressing that gap with the case study of Costa Rica.

This paper first estimates the NDP's black carbon and methane emission mitigation potential, disentangling the effect of stated measures. We use established long-term energy and land-use planning tools adapted to estimate SLCPs. Then, we identify the impact of the mitigation measures in the NDP and other sectoral plans on the value chains of transport, industry, solid waste, and livestock activities. We also extract instruments from such existing policy documents. Our value chain analysis examines the activities required to bring goods or services from inception to use (FAO and UNDP, 2020; Ndiritu, 2020). Furthermore, we consult stakeholders to identify instrument implementation barriers, and we score instruments according to their potential for synergy across sectors. Our synergy identification can help Costa Rica, and other countries formulate climate policy instruments integrated with SLCP mitigation.

The paper continues as follows: Section 2 describes the methods, Section 3 presents results, Section 4 discusses the policy relevance of the results, and concludes the paper.

2. Methods

We develop an analytical framework, summarized in Fig. 1, that combines quantitative and qualitative methods to respond to the question: *what intended policy instruments should the Costa Rican Government*

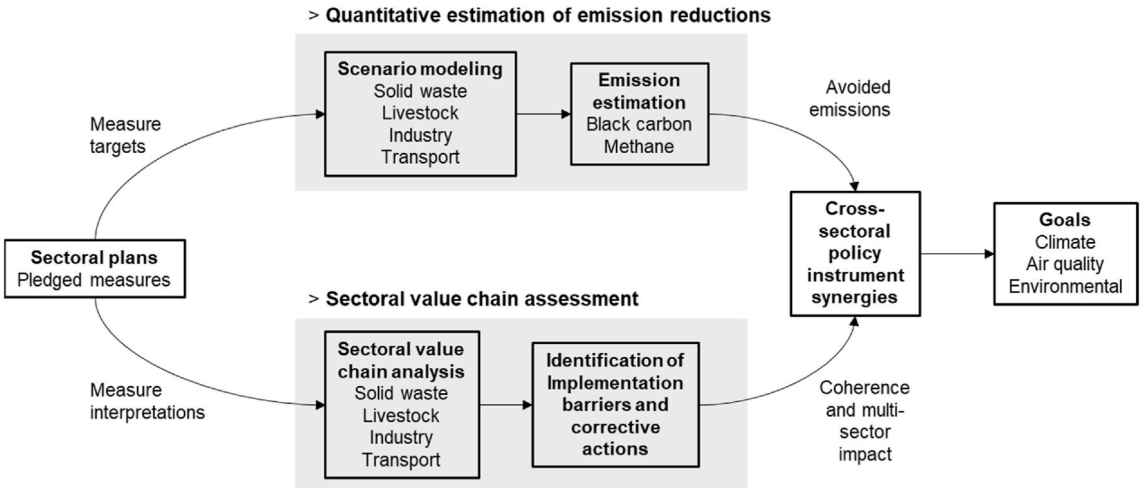

Fig. 1. The analytical framework to assess SLCP mitigation measures and policy instruments in Costa Rica.

prioritize to maximize SLCP emission reduction? We first model the emission reduction impact of the NDP's mitigation measures and policy objectives since it is the principal climate policy programmatic document of Costa Rica (see Supplementary Table 2 for the other reviewed documents). We then review existing programmatic documents and sectoral policies for the transport, industry, solid waste, and livestock economic sectors responsible for most SLCP emissions (MINAE, 2021) to extract the specific nationally planned instruments and their timelines for implementation.

The analysis has two parts: a quantitative emission trajectory modeling (top block, Fig. 1) and a qualitative sectoral value chain assessment (bottom block, Fig. 1). We develop the latter through expert interviews with public sector experts who identify barriers, an approach similarly used in (England et al., 2018; Gerlak et al., 2021). Below we show further details of the two parts.

The quantitative modeling and qualitative value chain assessment identify policy instruments that advance specific mitigation measures. By comparing all the identified policy instruments, we find the ones that advance multiple policy objectives across sectors, i.e., cross-sectoral synergies. Economy-wide models (e.g., General Equilibrium Models) can represent complex dynamics resulting from policy instruments. However, the aim of this paper is different: to identify such instruments in the first place. Moreover, the technical detail of the scenario analysis presented in this paper is better suited than an economy-wide model to represent future technological and behavioral change, which ultimately drives SLCP emission reduction potential.

2.1. SLCP emission estimations

Table 1 shows SLCP historical values. Black carbon emissions are present in the energy sector, the agriculture, forestry, and land use (AFOLU) sector, and waste sector. However, we estimate black carbon only for fossil fuel combustion in the energy sector since it represented about 88% of black carbon emissions in 2017 (MINAE, 2021). Although not modeled here, preventing forest fires and enforcing waste management instruments would also avoid black carbon emissions in the AFOLU and waste sectors, representing about 12% of total black carbon emissions in 2017 (MINAE, 2021). Methane is quantified in most national GHG inventories, including in Costa Rica. In 2017, solid waste and livestock represented more than 70% of the national total anthropogenic methane emissions (MINAE, 2021). Hence, we focus our methane estimations on those two sectors. For both SLCPs, the estimations range from 2018 to 2050, a period compatible with the calibration of existing decarbonization analysis models and the implementation timeframe of the NDP.

Table 1
Short-lived climate pollutant historical emissions [kt].

	2010	2012	2015	2017
Energy sector black carbon (BC) emissions	N/A	N/A	1.78	1.76
AFOLU biomass burning black carbon emissions	N/A	N/A	0.203	0.198
Waste burning black carbon emissions	N/A	N/A	0.048	0.047
Livestock methane emissions	91.9	95.1	83.6	89.8
Solid waste methane emissions	50.75	53.16	55.8	56.77

Source: (MINAE, 2021).

To estimate black carbon emissions from transport and industry, we follow a tier 1 approach in which an activity variable is multiplied by an emission factor. Here we assume emission factors (see Supplementary Table 1) for transport similar to the European vehicle fleet in 2005, corresponding with the lowest value suggested in the *EMEP/EEA air pollutant emission inventory guidebook* (European Environment Agency, 2019). We extract average emission factor values from the guidebook for stationary fossil fuel consumption; we extract the lowest value for biomass consumption.

We obtain fuel consumption data using scenario simulations in the Open-Source Energy Modeling System for Costa Rica (OSeMOSYS-CR) (Godínez-Zamora et al., 2020), based on the OSeMOSYS system (Howells et al., 2011). These simulations comprise the transport and industry sectors (i.e., the energy consumption component of industry). Industrial process emissions are out of the scope of this study. Although clean cooking fuels are considered an important measure globally to reduce black carbon and improve air quality (Rao et al., 2013), Costa Rica's high electricity and liquified petroleum gas access for cooking make other sources more relevant. For example, according to the black carbon emissions inventory for 2015, 80% come from fuel combustion in industry and transport (Instituto Meteorológico Nacional, 2019).

For methane estimations, we use the equations below. Equation (1) shows the generated solid waste GSW_t, which grows with GDP per capita and a yearly reduction generation coefficient (RG) that changes the unit generated solid waste per capita $UGSW_{t-1}$ in the previous year (all exogenous inputs). We generated the trajectories starting in 2018 with a value of 0.81 kg/person/day, based on a local study supporting the formulation of a nationally appropriate mitigation action for the waste sector (GFA Consulting Group, 2019). Equation (2) shows the estimation of methane emissions from solid waste, which depends on the emission factor (EF) (see Supplementary Table 1), the generation of solid waste (GSW), and the retrieved methane from landfills (RCH_4).

$$GSW_t = UGSW_{t-1}\left(\frac{GDP\ per\ capita_t - GDP\ per\ capita_{t-1}}{GDP\ per\ capita_{t-1}}\right)(1-RG)\left(\frac{Population_t}{1000}\right) \quad (1)$$

$$\mathrm{ECH4}_{waste,t} = \mathrm{EF}_t * GSW_t * (1 - \mathrm{RCH4}_t) \quad (2)$$

Livestock emissions are estimated with an OSeMOSYS-based Climate Land Energy and Water (CLEW) model for Costa Rica (Quirós-Tortós, 2020). CLEW is a framework for the integrated assessment of resource systems using quantitative tools used in many countries to develop integrated decarbonization pathways (Ramos et al., 2021). Costa Rican CLEW's model was developed with local information provided by stakeholders during the updating process of the country's Nationally Determined Contribution (NDC). It includes a detailed model of the agricultural sector. Emissions are calculated according to Equation (3), estimating emissions as a function of unit output per animal (UOA), animal load per hectare (AL), and grazing land coverage (GLC) for meat, milk, or mixed production (all exogenous inputs). We separate manure and enteric fermentation livestock emissions for milk and meat production (see Supplementary Table 1 for base emission factors).

$$\mathrm{ECH4}_{livestock,t} = \mathrm{EF}_t * \mathrm{UOA}_t * AL_t * GLC_t \quad (3)$$

2.2. Scenarios

To analyze SLCP mitigation measures, we developed scenarios. Table 2 shows the scenarios developed with OSeMOSYS-CR for the energy sector and the corresponding black carbon estimations. The columns *Mitigation Measure* and *Policy Objectives* correspond, and each row constitutes one scenario. The *Full decarbonization description* column description shows the assumptions, per measure, to model the complete NDP. Notice that, for simplicity, some measures are not applied to the NDP scenario.

Besides the mitigation scenarios, we create a business-as-usual scenario, i.e., the BAU. In the energy sector, the BAU maintains high use of private transport, very low transport electrification, a constant demand-GDP ratio, and a 3% GDP growth after 2023 (affects Equation (1) and the OSeMOSYS-CR model). It also keeps the industry sector dependent on fossil fuels. Although the NDP suggests multiple mitigation measures, it is only explicit about some zero-emission vehicle mitigation targets. Other policy objectives are taken from previous NDP assessments (Godínez-Zamora et al., 2020; Groves et al., 2020) or based on expert criteria.

Table 3 describes the scenarios for methane estimation in the livestock and solid waste sectors. Livestock directly emits methane from manure and enteric fermentation. However, land requirements for production cause deforestation and CO_2 releases. Other important livestock measures are increasing meat and land production per unit of land, i.e., a combination of protection, management, and restoration policies. As a result, more compact production schemes would meet societal demands with less deforestation and more land for reforestation, avoiding carbon emissions (Drever et al., 2021; Griscom et al., 2020). Fattening cattle is often recommended for livestock to decrease the number of animals per kg of output produced (Ndiritu, 2020), keeping emissions more or less constant. However, better feed and animal management can reduce methane emissions between 0.1 and 1.2 Gt CO_2e per year globally (Roe et al., 2019).

Demand-side measures like diet changes and food waste reduction were not explicitly modeled. Costa Rica has a meat food supply per capita lower than Central America, Mexico, and South America: 52.6 kg/capita/year in 2019 compared to 62, 70, and 83, respectively (FAO, 2022). The literature proposes ambitious scenarios where beef consumption increases in Central American and Caribbean countries (Dumas et al., 2022). Hence, while dietary change is an important instrument to reduce methane worldwide, there are insufficient studies in Costa Rica to model it, and it may be more critical in countries where the meat supply is high. Food waste reduction is implicit in the reductions of per capita solid waste generation.

The CLEW model -used to model livestock-assumes the production per unit of land (or productivity, in kilograms of meat per hectare, resulting from the multiplication of UOA and AL in Equation (3)) for meat will increase 11% by 2030 and 20% by 2050 relative to 2018; for milk, it will increase 12% by 2030 and 24% by 2050. These productivity increases translate into similar production growth without demanding more land: meat production increases 12% by 2030 and 25% by 2050 relative to 2018. Similarly, milk production will increase 13% by 2030 and 27% by 2050 (Quirós-Tortós, 2020). The productivity improvements are caused by better feed and animal management, while the meat industry maintains net meat exports (Quirós-Tortós, 2020).

The CLEW model assumptions are based on the National Livestock Strategy (MAG, 2015) and consultations with local stakeholders (Quirós-Tortós, 2020). The BAU keeps the same emission factors as the base year (2018), and production keeps up with the growth of GDP and population. The scenario description for the solid waste sector in Table 3 can be directly traced to Equations (1) and (2). The methane capture

Table 2
Modeling inputs of black carbon scenarios to model transport and industry in OSeMOSYS-CR.

Energy system component	Mitigation Measure	Policy Objectives	Full decarbonization description
Heavy freight fleet composition	Zero-emission vehicle (ZEV) penetration in freight transport	30% in 2035 and 85% in 2050	10% by 2030 and 98% by 2050 with electric and hydrogen technologies
Light freight fleet composition			5% by 2030 and 50% by 2050 with electric technology
Fleet composition	ZEV in public transport	30% in 2035 and 85% in 2050	30% by 2035 and 85% by 2050 with electric technology. 3% by 2035 and 10% by 2050 with hydrogen buses
	ZEV in private transport	30% in 2035 and 95% in 2050.	35% by 2035 and 99% by 2050 with electric technologies
Boilers, heat production, lift trucks, and on-site power generation	Industry decarbonization	Substitutes oil products with biomass and electricity by 2050	
Demand	Average yearly distance driven	Apply 10% reduction to passenger and freight driving distances by 2050	Not applied
	Freight rail	Transport 20% of heavy freight demand in 2050, increasing linearly every year starting in 2024	
	Freight elasticity to GDP reductions	Decrease the demand elasticity to GDP by 10% in 2030	Not applied
	Passenger elasticity to GDP reductions		Not applied
	Mode shift and passenger rail transport	Increase its participation in motorized transport by 7.5% in 2035 and 20% in 2050 It reduces motorized transport by 4% in 2035 and 10% in 2050 relative to BAU Transports 0.1 Giga passenger-kilometers and enables public passenger transport mode shift	

Table 3
Modeling of methane scenarios for this analysis.

Sector	Scenarios	Objectives
Livestock	Full decarbonization	The emission factor (EF in Equation (3)) of manure and enteric fermentation will drop about 15% by 2030; the reduction will reach almost 43% by 2050. The reductions start in 2023 due to sustainable farm management.
	Measures delayed until 2030	The emission factors (EF) will decrease 33% by 2050, starting in 2031.
	50% of mitigation effects	The emission factors (EF) will decrease 7.5% by 2030 and 25% by 2050. The reductions start in 2023.
	Measures delayed until 2040	The emission factor (EF) will decrease by 18% by 2050, starting in 2041.
Solid waste	Full decarbonization	The per capita solid waste generation (GSW in Equations (2) through RG in Equation (1)) decreases 3% yearly. The emission factor for landfills decreases 2% annually (EF in Equation (2)). Methane recovery from landfills (RCH4 in Equation (2)) will reach 40% by 2050. These variables start changing in 2024.
	Per capita reduction with composting and methane capture	The per capita solid waste generation (GSW) decreases 2% yearly. The landfill emission factor (EF) decreases 1% annually (due to composting, organic matter in landfills decreases). Methane recovery from landfills (RCH4) will reach 40% by 2050.
	Per capita reduction with composting	The per capita solid waste generation decreases 2% yearly (GSW). The emission factor (EF) for landfills decreases 1% annually.
	Per capita reduction	The per capita solid waste generation (GSW) decreases 2% yearly
	Least ambition	The emission factor (EF) for landfills decreases 1% annually

component can be used to generate electricity or heat, but these applications were not modeled.

2.3. Sectoral value chain assessment and identification of synergies

The quantitative analysis described in Section 2.1 identifies the potential black carbon and methane emission reductions from the NDP. However, there is no guarantee that the emission reductions will be achieved within the specified timeframe. Implementing mitigation measures that reduce SLCP emissions requires policy instruments and overcoming barriers. Furthermore, the NDP is influenced by other sectoral plans that include actions that would indirectly mitigate GHG and SLCP emissions, e.g., developing railway transport. Supplementary Table 2 shows a list of plans per sector, and Supplementary File 1 shows the list of actions (combining mitigation measures and policy instruments) suggested by the plans.

The second component of the analytical framework outlined in Fig. 1 aims to assess how specific policy instruments could implement each mitigation measure. Other instruments can also overcome mitigation measure implementation barriers. The second component requires a value chain analysis for each sector: transport, agriculture and land-use, solid waste, and industry. Value chain assessments can identify where interventions are needed to implement a mitigation measure (Habert et al., 2020) and facilitate expert assessment on whether a measure accomplishes low emissions, climate change resilience and socio-economic development (Hasan et al., 2020). Our policy instrument assessment follows these steps:

1. **Instrument identification:** identify if the action from Supplementary File 1 is a policy objective describing a target or a policy instrument, i.e., a mechanism to modify the value chain. If the action is a policy objective, define an instrument to achieve the objective. These are henceforth referred to as *nationally planned instruments*. Specify when the instrument should be implemented according to the plan: short (by 2022), mid (by 2030), or long-term (by 2050). Here, we define the periods according to the National Decarbonization Plan. Short-term instruments could be under implementation or have been delayed.
2. **Instrument classification**: classify the instruments into i) *regulation*, ii) *governance* through institutional capabilities, iii) *fiscal* policy, iv) *planning* as a knowledge and decision-making tool, v) *investments,* and vi) transformations of *business operations.* Instruments with multiple features can have multiple classifications. The governance classification applies to instruments related to how, why, and with what implications collective affairs are managed (Bulkeley, 2010), requiring better institutional capabilities, i.e., the heuristics, skills, and routines of the involved organizations (Carney et al., 2016).
3. **Value chain pairing:** define what components of the value chain the instruments have an incidence on; use the value chains in Fig. 2 for the sectors of interest. Afterward, describe how the nationally planned measures are distributed in the value chain.
4. **Barrier identification and classification:** identify the barriers of each nationally planned instrument using expert opinions via stakeholder consultation. Classify the barriers as cultural, economic, technical, legal, political, or institutional. Barriers with multiple features can have multiple classifications. Define additional *instruments proposed by authors* for each barrier to overcome or mitigate the identified barriers.
5. **Instrument scoring:** quantify a score for each instrument based on mitigation potential and synergy effect. For the synergy effect, score instruments according to Table 4. The instruments with high positive scores cause positive synergies; the converse is true. Consider how the instruments could affect the value chains to justify the score.
6. **Synergy identification:** find common instruments (either stated in the programmatic documents or helpful for overcoming barriers) that meet multiple functions across the four sectors' value chains. Use the synergy score to identify the measures that cause the highest synergies within that sector, and review similarities with similar instruments in other sectors.

For the "barrier identification and classification" step, the task of the interviewed experts was to respond to questions in a written questionnaire, presented in a virtual meeting, and later filled out asynchronously. The questions were:

1. What barriers may prevent the full implementation of mitigation measures?
2. What are the unidentified measures, projects, or programs in the value chain that your institution is currently carrying out?
3. What measures will your institution include in its next action plan?
4. In your opinion, what are additional measures that could increase the ambition of SLCP mitigation?

The experts were affiliated with public sector institutions that oversee SLCP-emitting sectors (transport, agriculture, and waste): the Ministry of Planning and Economic Policy (all sectors), the Ministry of Health (waste sector), the Ministry of Agriculture and Livestock (agriculture sector), the Direction of Environmental Quality at the Ministry of Energy and Environment (all sectors), and the Ministry of Transport and Public Works (one sector). These institutions are representative of the sectors in the public sector apparatus, but the authors recognize that the private sector should participate in future exercises.

Our approach identifies the instruments with high synergy scores that could benefit multiple sectors. Other studies quantify a centrality metric to identify such synergies (Li et al., 2019) or network analyses

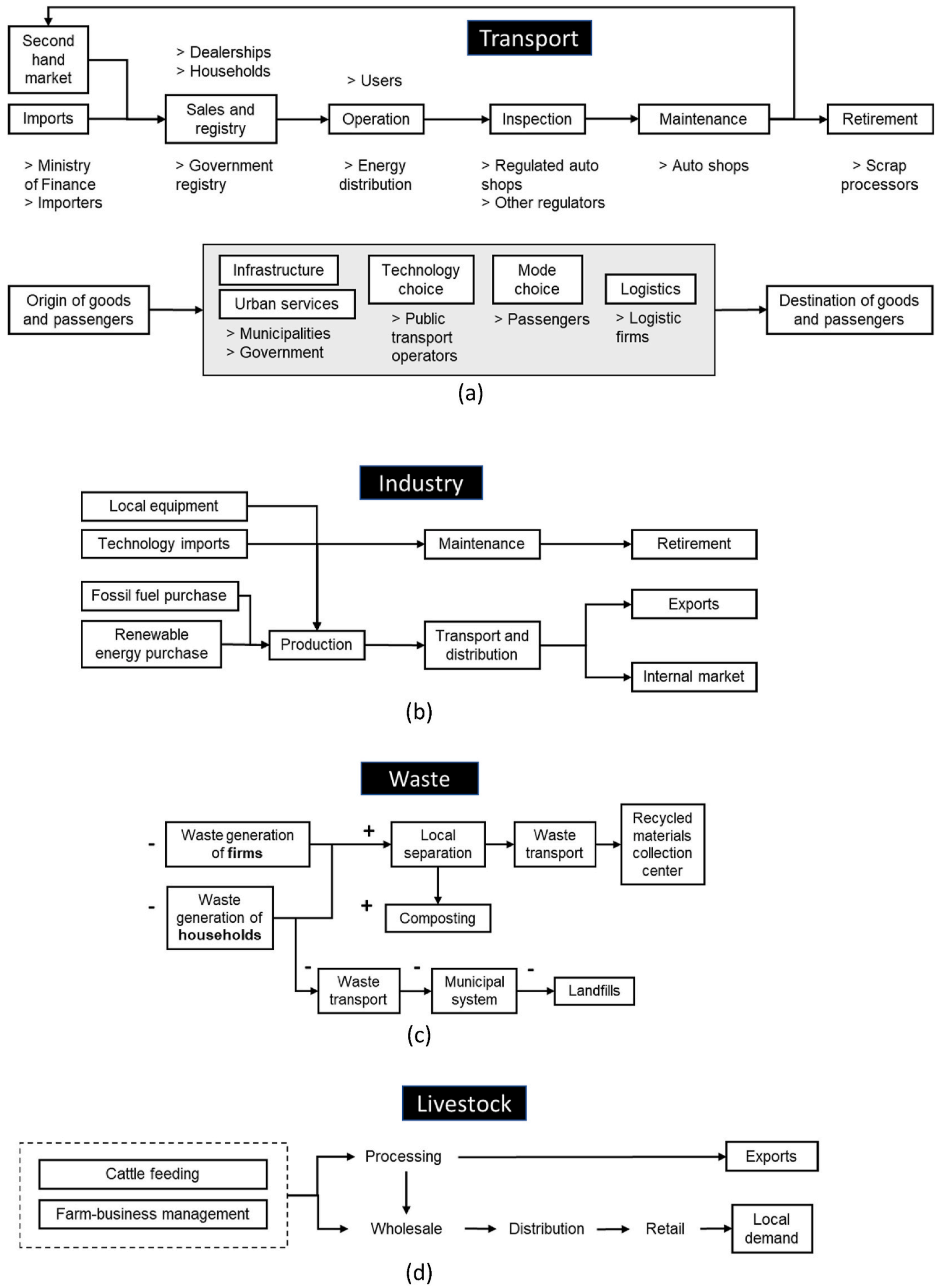

Fig. 2. Sectoral value chains for a) transport, b) industry, c) solid waste, and d) livestock.

(Mainali et al., 2018; Weitz et al., 2019). Here we score how an instrument is linked to achieving another goal according to Table 4—the scoring results from the best judgment of the authors and the value chain analysis of each instrument (the detailed scoring justification per instrument is in Supplementary File 2). Furthermore, we judge whether an instrument anticipated for a sector may also benefit another, creating cross-sectoral synergies. For example, one commonly identified barrier is the siloed structure of ministries and government agencies (Medina Hidalgo et al., 2021). Hence, considering the collaboration potential across sectors in institutional reforms can overcome such a barrier. While other studies have analyzed the synergies between two instruments through theoretical modeling and empirical case studies (van den Bergh et al., 2021), our approach evaluates multiple instruments.

A concept broader than synergy identification is climate policy integration, which requires a comprehensive understanding of value chains (Medina Hidalgo et al., 2021). Climate policy integration has challenges for implementation (Medina Hidalgo et al., 2021): incompatibility between short-term and long-term goals, the prevalence of economic interests over environmental ones, lack of legislation, and competing rules across sectors and jurisdictions. Legislation and rules

Table 4
Interaction score for instrument comparison (Madurai Elavarasan et al., 2021; Nilsson et al., 2016).

Score	Criteria
+3	Inextricably linked to the achievement of another goal (indivisible)
+2	Aids the achievement of another goal (reinforcing)
+1	Creates conditions that further another goal (enabling)
0	No significant positive or negative interactions (consistent)
−1	Limits options on another goal (constraining)
−2	Clashes with another goal (counteracting)
−3	Makes it impossible to reach another goal (cancelling)

shape existing organizational structures, carrying parallel planning processes. Moreover, political change can derail the progress of long-term plans. Hence, our analysis also defines instruments (proposed by the authors) that can overcome the identified barriers. For instance, regulatory proposals, like internal combustion engine car bans (i.e., legal prohibitions), may lack enforcement power (Plötz et al., 2019). Such bans need laws or large financial penalties to be effective at removing emissions by 2050 (Plötz et al., 2019). On the downside, bans are politically unpopular, and other policies are needed, e.g., increasing transit efficiency (Plötz et al., 2019).

Typically mentioned instruments that can overcome barriers are data collection and monitoring systems, training and capacity building, communication and dissemination of best practices, and private sector engagement (Malley et al., 2021).

3. Results

3.1. SLCP emissions from pledged measures

Table 5 shows the SLCP emission estimations of the BAU and full decarbonization scenarios with all measures as defined in Table 2. When considering biomass (see Fig. 3a), the black carbon emission estimations are higher than without it (see Fig. 3b). Black carbon emissions from biomass could be acceptable in the energy sector because the source does not emit CO_2; biomass consumption could increase if it becomes a cost-effective decarbonization option. Without considering biomass, decarbonizing the energy sector would reduce black carbon emissions by 20% by 2030 and 85% by 2050, relative to 2018 levels. Industry coke would cause over half of the black carbon emissions by 2050 (see Fig. 3b), followed by agriculture diesel which has no modeled substitutes (22%, see Fig. 3b). Residual diesel consumption in the transport sector will cause the remainder of emissions (see Fig. 3b). Under the BAU, black carbon emissions will increase by more than 70% by 2050 (see Fig. 3).

Livestock methane emissions have fallen since 2010, but waste emissions have risen (see Table 1). Under the BAU, livestock methane emissions will increase 26% by 2050 relative to 2018 (see Fig. 4a). Under the decarbonization assumptions, livestock emissions will fall 28% by 2050 relative to 2018. Although emission reductions by 2030 are only 5% under the decarbonization of livestock, it is 17 percentage points lower than under the BAU (see Fig. 4a). Supplementary Table 3 shows the breakdown of the livestock emission reductions in enteric fermentation and manure. Solid waste emissions would more than double under the BAU by 2050 relative to 2018 but more than halve in the same under the decarbonization scenario (see Fig. 4b).

Table 6 shows the breakdown of emission reductions for each mitigation measure, each associated with one or multiple policy objectives. The full decarbonization scenarios do not necessarily accumulate the avoided emissions because of the scenario definitions (see Section 2.2.). The measures are ranked in descending order, normalizing the avoided emissions of a complete decarbonization scenario. Reducing diesel from freight and public transport rank first and second in avoided black carbon emissions, followed by private transport and industry. The remaining measures, if done alone, score less than 10 (i.e., 10% of the total mitigation potential). To mitigate black carbon, reducing diesel consumption is the most relevant action. Therefore, increasing public transport alone (i.e., without electrification and keeping diesel reliance) would increase black carbon emissions, despite decreasing GHG emissions (see Fig. 5).

Supplementary Table 4 shows more disaggregated black carbon avoided emission results by the energy subsector, where heavy freight diesel is the highest source of avoided emissions, followed by light freight. While freight rail and freight demand reduction (e.g., through logistics) do not have a high score if implemented alone, they comprise more than 20% of the total mitigation potential in heavy freight. Future work should consider the economic benefit of the measures in their relative importance.

Methane reductions from livestock are evaluated simultaneously, but Table 6 shows the effects of delaying the enforcement of such measures. Delaying measures until 2030 has the same effect on cumulative emissions as targeting half of the mitigation effects. Therefore, it is crucial to advance livestock mitigation as soon as possible. Delaying measures until 2040 would only avoid 15% of the emissions that the complete livestock decarbonization scenario could.

Table 6 shows different levels of ambition in mitigating solid waste emissions (see Table 3 for the scenario description). A combination of per capita waste generation reduction, emission factor reduction from more composting practices, and retrieving methane from landfills produces the highest mitigation potential. Only increasing composting with a performance of a 1% reduction in the emission factor would result in 25% of the mitigation potential.

3.2. Value chain analyses

This section describes policy instruments explored in the qualitative analysis. Fig. 6 exemplifies how the actions stated in four different plans to mitigate freight transport emissions affect the respective transport value chain. In this example, all of the actions are policy instruments. Some actions affect the entire value chain (systemic actions), while others affect specific parts of the value chain. The complete list of policy instruments in Supplementary File 1 consolidates the instruments across plans and filters repeated or ambiguous actions. In general, we find that the plans in Supplementary Table 2 are coherent in vision but not necessarily concrete. The spreadsheets containing the instrument-by-instrument analysis are in Supplementary File 2; the results presented in this section summarize the complete analysis.

Fig. 7a shows the number of the identified policy instruments by sector: 33 for public transport, 7 for private transport, 22 for freight, 6 for industry, 29 for waste, and 21 for AFOLU. Fig. 7b shows the number of value chain components by sector, detailed in Supplementary Figures 8 and 9. 55% of the evaluated policy instruments are nationally planned; the remainder 45% of actions are proposed by the authors to

Table 5
Short-lived climate pollutant estimations [kt].

	2018 estimation	2030 BAU	2030 Full Decarbonization	2050 BAU	2050 Full Decarbonization
Energy sector black carbon (BC) emissions	1.2	1.4	1	2.1	0.4
Energy sector BC emissions (without biomass)	1.1	1.2	0.8	1.8	0.15
Livestock methane emissions	80	90	77	101	58
Solid waste methane emissions	60	78	51	141	27

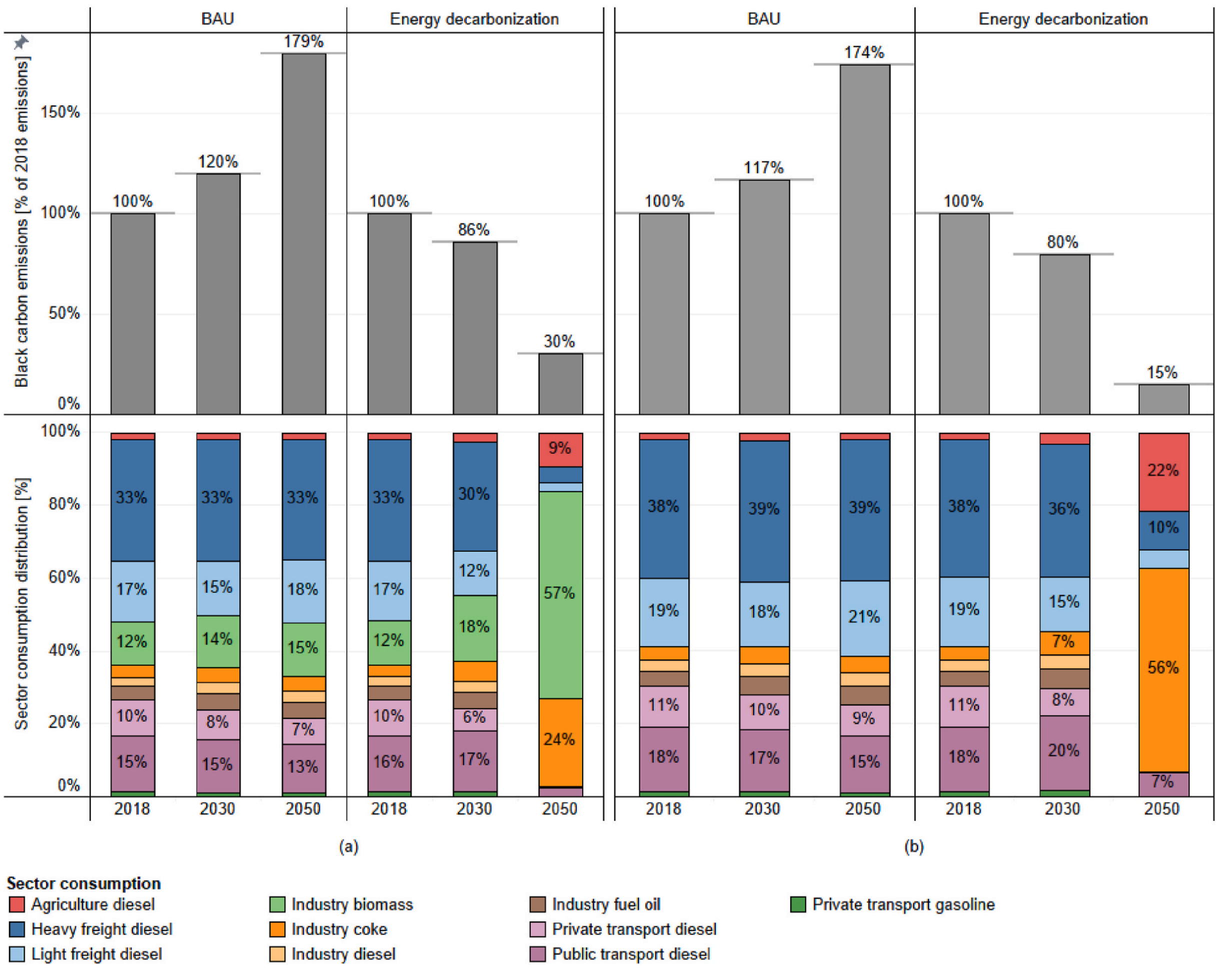

Fig. 3. Long-term estimation of energy sector black carbon emissions and contribution of major sources. a) Considering black carbon emissions from biomass. b) Without black carbon emissions from biomass.

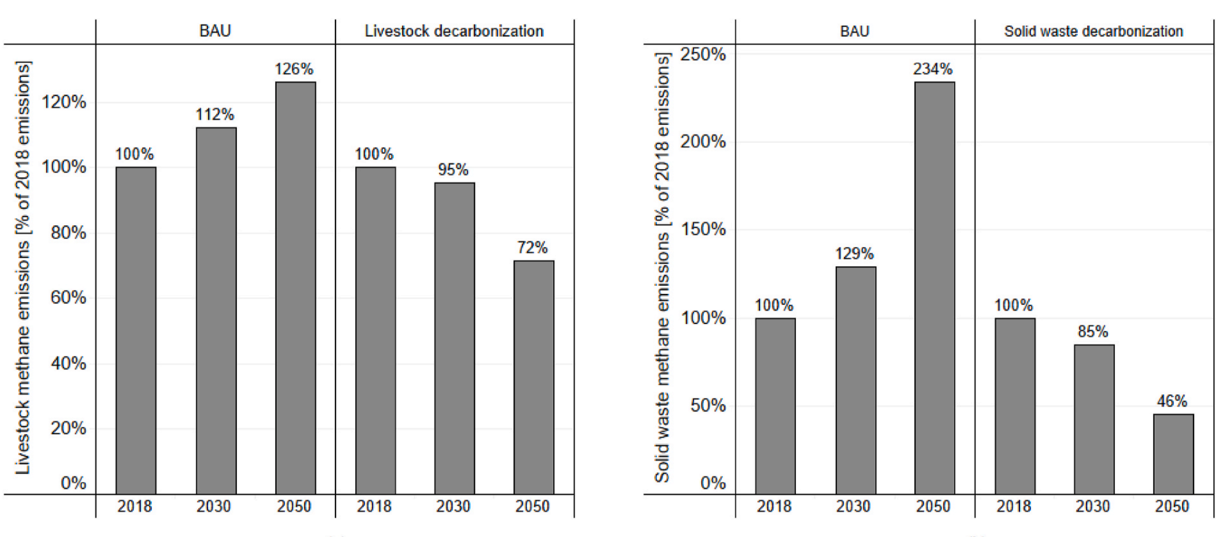

Fig. 4. Long-term estimation of methane emissions. a) Livestock sector. b) Solid waste sector.

overcome the barriers (see Fig. 7c for the distribution by sector). Fig. 7d shows the distribution of the planned time frames of instruments per sector. We select the category "*all*" if the action does not specify when to implement or appears across periods.

Public transport has the highest number of short-term instruments, emphasizing the importance of planning exercises, investments, and public transport improvements to catalyze more efficient transportation quickly. The Freight, Waste, and AFOLU sectors also have more short-

Table 6
Emission reduction potential in 2050 for the scenarios described in Section 2.2.

Short-lived climate pollutant	Measure	Avoided cumulative emissions in 2022–2050 [kt of SLCP]	Score [relative to highest ambition]
Black carbon from the energy sector incomplete combustion	Energy full decarbonization	25.2	100
	Zero-emission vehicle (ZEV) penetration in freight transport	15.6	61.7
	ZEV penetration in public transport	9.4	37.1
	ZEV penetration in private transport	6.6	26.3
	Industry decarbonization	3.2	12.6
	Distance reduction	1.8	7.0
	Freight rail	1.7	6.8
	Freight demand elasticity to GDP reduction	0.8	3.0
	Passenger demand elasticity to GDP reduction	0.2	0.9
	Mode shift and passenger rail transport	−1.6	−6.4
Methane from livestock	Livestock full decarbonization	660	100
	Measures delayed until 2030	387	58.6
	50% of mitigation effects	344	52.1
	Measures delayed until 2040	100	15.2
Methane from waste	Solid waste full decarbonization	1507	100
	Per capita reduction with composting and methane capture	1166	77.4
	Per capita reduction with composting	961	63.8
	Per capita reduction	701	46.5
	Least ambition	382	25.4

term instruments than other instruments. Private transport does not have short-term instruments because of the fiscal incentives Costa Rica already has in place. The industry sector has the least number of measures, and none are specified as short-term, reflecting the emerging understanding of what to do in that sector and the difficulty of committing to transformations amid the current economic crisis.

Fig. 8 shows the overall distribution of instrument classifications and barriers types. Fig. 8a shows that most instrument classifications are *planning* exercises with 39%, followed by *governance* with 22%. Barriers characteristics are one-third institutional and one-third economic (see Fig. 8b). Fig. 8c shows that most proposed instruments against barriers are planning exercises. Hence, the main functions of the proposed instruments are planning how to re-organize and enable institutions to apply instruments and overcome economic obstacles to low-carbon technology investment.

Supplementary Figure 1 shows how barriers, nationally planned instruments, and proposed by authors instruments are distributed in time. Nationally planned instruments in the long-term are mainly investments, but in the short-term are increasing enforcement through improved governance. In the mid-term, *planning* is the classification with the most appearance for nationally planned instruments, including municipal regulatory and urban development plans. Such plans should result in regulations that would mainly benefit public transport and waste sector mitigation action. The sector with the highest planning requirements is freight. It reflects its difficulty in addressing freight decarbonization with international trade components (political and institutional barriers) and lack of technology and capital (technical and economic barriers). Supplementary Figures 2 to 7 show each sector's barriers and instrument classification by value chain component and provide the following insights:

- Public transport (Supplementary Figure 2) faces cultural barriers in the destination and origin of passengers but can be overcome with effective urban planning. In early adoption, bicycle lanes and exclusive bus transit lanes can cause traffic jams, which means that attention to the technical pertinence of these measures at the city-planning level is necessary. From the transport-as-a-service perspective, most instruments point to investing in and providing good urban services.
- In private transport (Supplementary Figure 3), transport access in rural areas is a technical barrier to electric vehicle adoption. The most apparent instrument to incentivize electric transport is fiscal measures in imports, sales, and registry components. The business

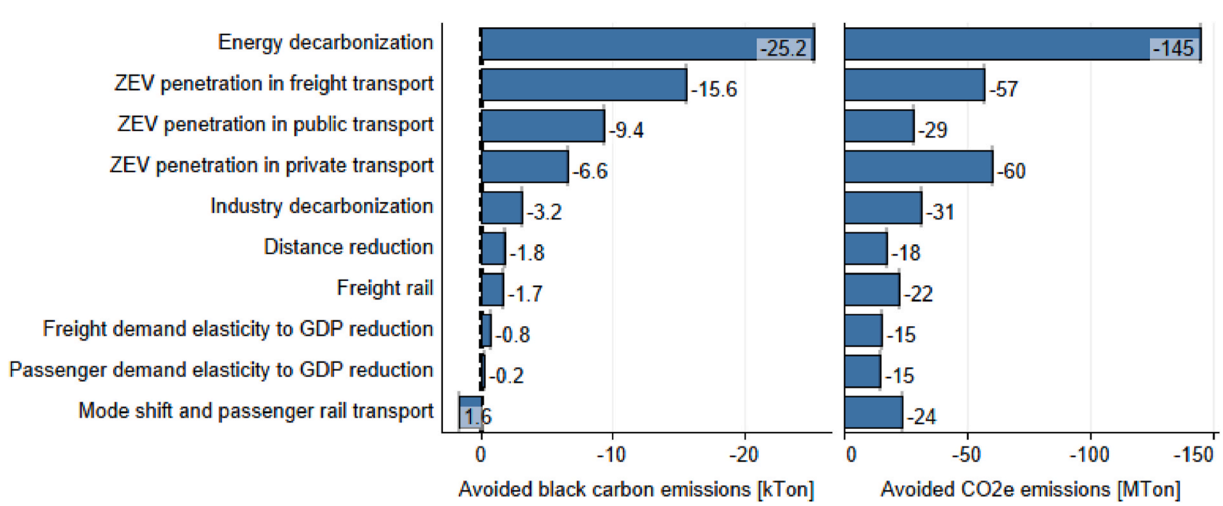

Fig. 5. Black carbon emission reduction compared to CO_2.

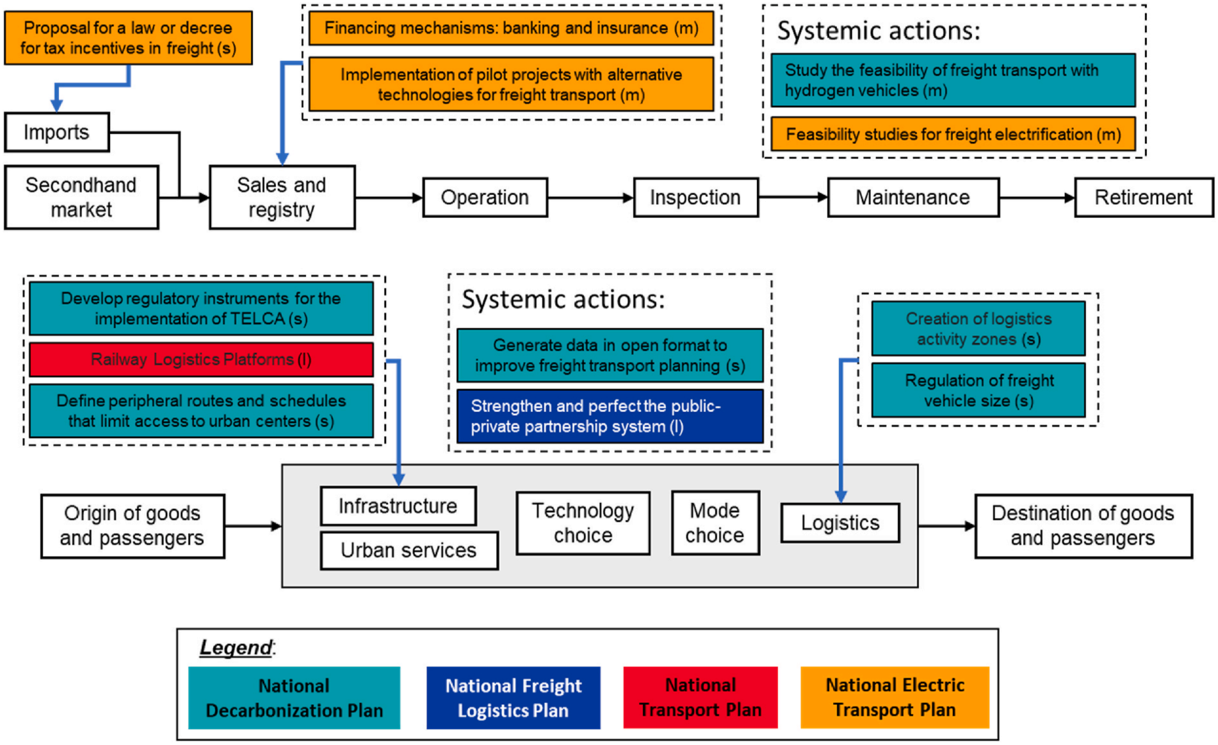

Fig. 6. Value chain analysis example for freight transport with short (s), mid (s), and long (l) term policy instruments stated in different sectoral plans mapped onto the value chain for freight transport.

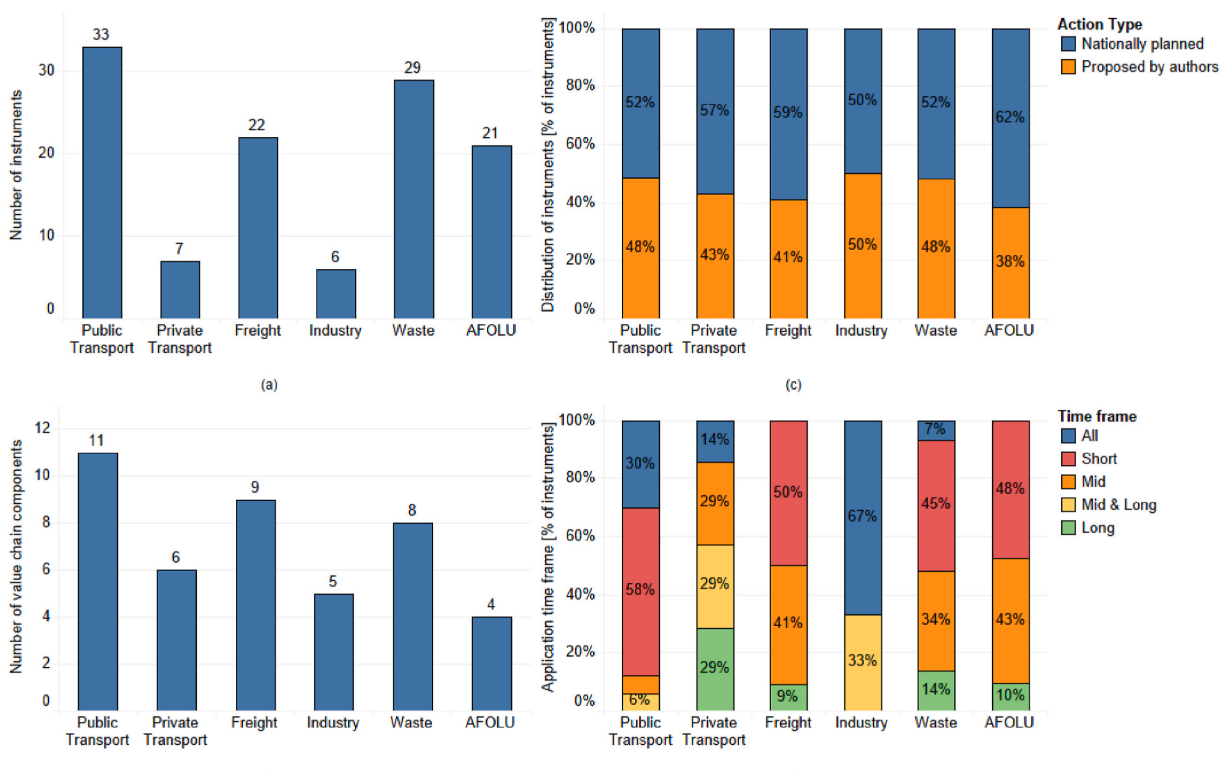

Fig. 7. Characteristics of policy instruments and value chains by sector. (a) Number of instruments by sector. (b) Number of value chain components by sector. (c) Distribution of instruments classified as nationally planned or proposed by authors. (d) Distribution of application time frames of instruments by sector.

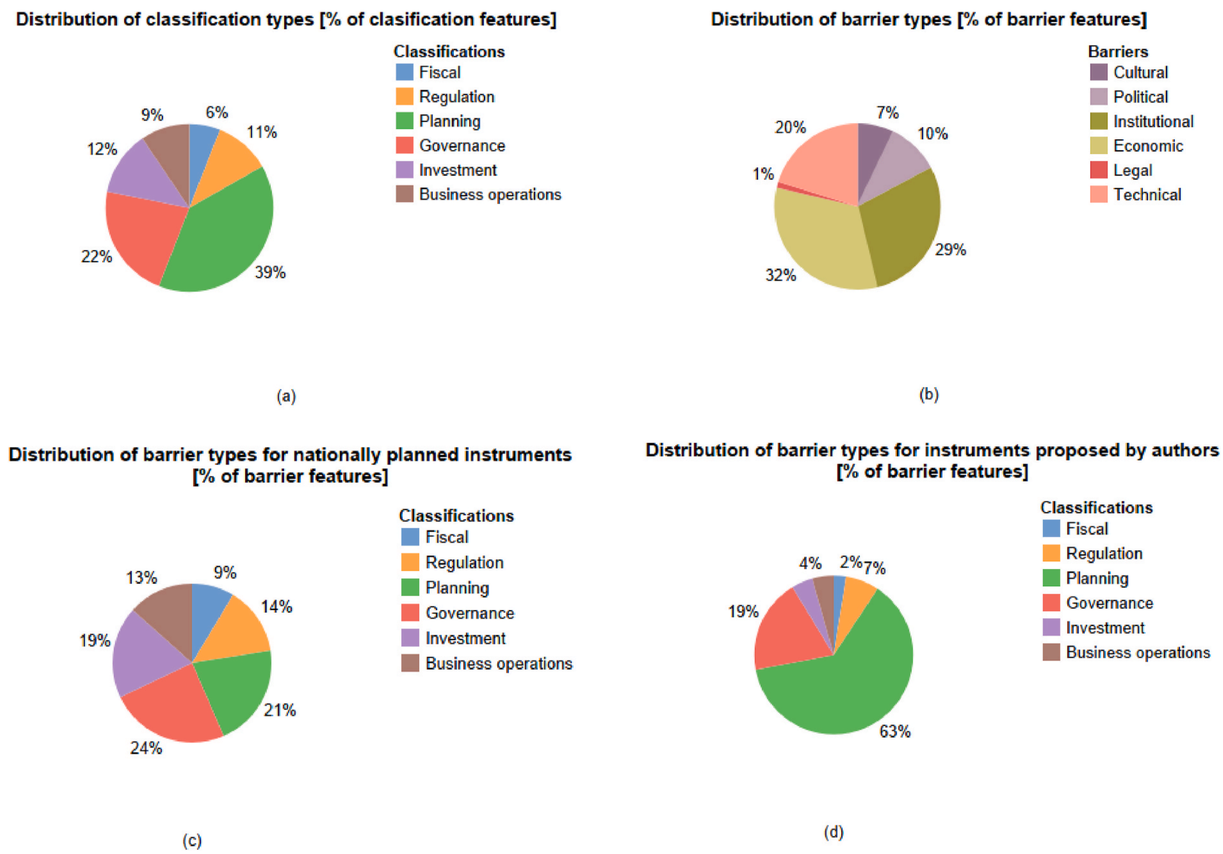

Fig. 8. Barriers and classifications across instruments. (a) Distribution of classifications for all instruments. (b) Distribution of barrier types. (c). Distribution of classifications for nationally planned instruments. (d). Distribution of classifications for instruments proposed by authors.

operations of banks should also facilitate private investment in this sector.

- In freight (Supplementary Figure 4), regulating trucks in cities can alleviate congestion and exposure to pollution, but improving logistics and operations (classifications with high appearance, will enable such regulatory stringency.
- The proposals suggest applying instruments to imports for fuel switching in freight and industry (Supplementary Figure 5), which face political, institutional, economic, and technical barriers.
- The solid waste sector (Supplementary Figure 6) has many classifications and barriers, mainly because it involves multiple actors across all of its value chain components.
- AFOLU focuses on farm-business management, which requires a shift in business operations to mainstream sustainable practices, with institutional support through enforcing existing strategies and creating technical capacity-building programs. These proposals mainly face economic barriers, like many other measures across sectors.

3.3. *Cross-sectoral policy synergies*

The value chain analysis does not define the most important policy instruments to pursue, but it provides information to justify if an instrument can advance mitigation in multiple sectors. Identifying which instruments cause the highest synergies across sectors will distill what reforms the government should prioritize to achieve mitigation. In the instrument-by-instrument analysis (detailed in Supplementary File 2), only the regulation of efficient vehicles has a negative score because it can facilitate the fleet renewal schedule of new combustion vehicles. Although newer combustion vehicles have higher emission standards (Kim Oanh et al., 2012), they do not avoid carbon dioxide emissions. Therefore, instruments that favor switching to zero-emission energy in transportation and industry can improve air quality and reduce GHGs (Sharifi and Khavarian-Garmsir, 2020), e.g., through hydrogen and battery-electric vehicle adoption (Machado et al., 2020).

Table 7 shows high-scoring instruments that can advance mitigation in multiple sectors. There are 14 nationally planned, 16 proposed by authors, and one that is both out of the 118 analyzed instruments, i.e., 26%. Table 7 shows instruments with at least a two-point score; 10 instruments score two synergy points, and 21 instruments score three synergy points (see Table 4 for synergy score meaning). We show the instruments according to combinations of classifications used in the value chain analysis.

Making zero-emission vehicles (ZEVs) less costly than internal combustion engine vehicles (ICEVs) through taxes creates high synergies for the three transport sectors; discouraging ICEVs through a carbon tax can also advance mitigation. In Costa Rica, private passenger electric vehicles (Evs) are, on average, already less costly than an ICEV (Quiros-Tortos et al., 2019), but other modes should be supported. Additionally, defining a taxation framework that encourages the development of a circular economy can provide the basis for a comprehensive environmental fiscal reform. For example, fiscal instruments for the circular economy can include raw material taxes, reuse/repair tax breaks, and a waste hierarchy tax at the end of the life of products (Milios, 2021). Each technological innovation stage has an effective fiscal instrument: subsidies for technological development and procurement for transformation (Pang et al., 2020).

An SLCP mitigation action plan should focus on exploring instruments that: i) consolidate the monitoring, report, and verification mechanisms of each sector into the *Sistema Nacional de Métrica de Cambio Climático* (SINAMECC) (i.e., a centralized climate governance data framework); ii) identify regional (i.e., Central American)

Table 7
Cross-sectoral policy instrument synergy identification.

Instrument classification (# of measures)	Score	Instrument (N: nationally planned |P: proposed by authors |N/P: both)		Public transport	Private transport	Freight	Industry	Waste	AFOLU	Num. of sectors
Fiscal (3)	3	Fiscal and financial conditions for zero-emission vehicle (ZEV) fleet	N	x	x	x				3
	2	Discourage internal combustion vehicles (ICVs)	N		x	x				2
		Implement a fiscal policy that incentivizes the development of a circular economy (i)	N					x	x	2
Planning (5)	3	Consolidate the sector's Monitoring Report and Verification and feed Costa Rica's National Climate Change Metrics System (SINAMECC)	N	o	o	o	o	o	x	6
		Identify regional development opportunities for zero-emission vehicle investments in Central America	P	o	o	x	o			4
		Explore the centralized coordination and financing (ii)	P	o				x		2
	2	Identify critical investments that enable electrification	P	o	x	o	o			4
		Private sector training on decarbonization technologies	P			o	x			2
Planning – Regulation (5)	3	Regulatory plans for densification, active and intermodal mobility, and consideration of waste management facilities	N/P	x				x		2
		Sectorization (iii)	N	x	o					2
		Include into urban planning the impact of freight and logistics to decrease congestion	P	o		x				2
		Municipalities identify critical routes where intermodal transport could produce high time savings. Then, they re-arrange routes, deploy cycling paths, and persuade buses to carry bicycles (iii)	P	x	o					2
Planning – Governance (8)	3	Information systems and technical support with information and communications technologies (ICTs)	N					x	x	2
		Dialogue with commercial partners for freight decarbonization (iv)	N			x	o			2
		A technical support program that provides continuous technological information to firms	N				o		x	2
		Improvement of national and cantonal roads (iii)	P	x		x				2
		Improve the effectiveness of infrastructure management agencies with governance reforms	P	o		x				2
	2	Explore compatibility of multiple information systems	P	o	o	o	o	x	o	6
		Fund pilot projects with international cooperation and devise scaling-up interventions	P	o	o	o	o	x	o	6
		Linkage mechanisms between vehicle parts companies, waste managers, and vehicle fleet owners	P	x				x		2
Governance (3)	3	Coordinate existing efforts of banking, insurance, private companies, academia, and public sector institutions to promote financing strategies for clean technologies	P	o	o	o	o	o	x	6
	2	Promote research and knowledge transfer between universities, government agencies, and private actors	P			o	o	x	o	4
		Municipalities and businesses partner together to promote the potential benefits of intermodality with bicycles to employees and customers	P	x	o					2
Investments (3)	3	Strengthen the logistics infrastructure to increase efficiency in the transfer of goods, considering public-private partnerships	N	o	o	x				3
		Identifying and establishing timely investments in infrastructure for electrification (v)	P	x	x	x				3
		Support economic recovery with urban planning investment, selecting key infrastructure to generate dynamism in cities. The prioritization of infrastructure can improve the efficiency of public spending.	P	x	o	o				3
Investment-Business Operations (4)	3	Public-private partnerships to electrify buses and other services	N	x	o	o				3
		Technology massification through financing at scale	N					x	x	2
		Development of advanced logistics systems	N	o		x				2
		Implement TELCA and other rail infrastructure	N	o		x				2
Business Operations (5)	3	Bank financing and insurance mechanisms (vi)	N	x	x	x			x	4

x: sector identified directly in the qualitative analysis
o: sector with synergy opportunity
(i) Includes biomass recovery from meat and milk value chains
(ii) The potential benefits are economies of scale, data intelligence, and geographical synergies. For example, waste collection accounts for +60% of solid waste management costs (Programa País Carbono Neutralidad Oficial del Gobierno de Costa Rica, 2017).

(iii) Also requires investment
(iv) Must consider the business operations of local and/or Central American firms
(v) Requires standards for construction that enable electricity supply for transport
(vi) Includes financial mechanisms to support agricultural businesses (AFOLU) with climate adaptation and mitigation features, insuring against disasters and unproductive practices.

development opportunities for ZEV investments, iii) explore the centralized coordination and financing of public transport and waste, iv) identify the critical specific investments that will enable transport and industry electrification -e.g., fast-charging stations (Victor-Gallardo et al., 2019)-, and v) provide training to the private sector on decarbonization technologies for freight and industry.

Planning exercises that result in regulation change include overhauling urban/municipal regulatory plans for densification, intermodal mobility, and waste management. Such reforms can couple with "*Sectorization*" (i.e., a change in bus routes for better connections between origins and destinations of transport users). Urban plans should also take into account freight logistics to reduce congestion. Since lack of funding and cultural resistance to change are barriers to these regulation changes, identifying high time-saving routes to encourage cycling lanes and bus usage can catalyze further changes. Adequate cross-sectoral urban planning facilitates the exchange of energy and materials in co-located households and businesses, reducing GHG emissions and air pollution (Ramaswami et al., 2017).

Institutions should be strengthened to carry out the following activities: i) develop and maintain information systems to gather data and promote decarbonization measures, ensuring compatibility amongst existing systems; ii) continuously conduct the dialogue with commercial partners for freight decarbonization; iii) improve infrastructure execution, particularly for roads; iv) fund pilot mitigation projects with international cooperation across sectors; v) coordinate all the ongoing mitigation actions across sectors, emphasizing linkages between waste manager, vehicle parts companies, and vehicle owners; vi) promote research amongst and information exchange across actors.

Identifying investments to enable electrification is important for governments to align their investment policy to attaining SDGs, avoiding wasteful projects, and public commitment to taxation (Thacker et al., 2019). Other investments that need to be prioritized are urban (e.g., roads, bridges, and train stations) to generate dynamism in cities and logistics to decrease freight transport costs. For example, road freight decarbonization can draw from route optimization (logistics improvements) and alternative energy carriers (Meyer, 2020). Once identified, the investments could be executed through public-private partnerships; currently, the government has a fiscally constrained space due to the COVID-19 pandemic and other structural causes, preventing high levels of new public spending. Despite the fiscal challenge, improving or maintaining effective vehicle inspection mechanisms to ensure high-emitting vehicles do not circulate is crucial to avoid deteriorating air quality (Kholod and Evans, 2016).

Businesses will also need to adapt their operations. For example, public-private partnerships can help electrify buses and freight but require changes in the respective business models, including the willingness to adopt advanced logistics systems. The private sector must also be willing to use rail infrastructure for freight, provided its cost-competitiveness. Finally, banks and insurance companies should adapt their rates for low-carbon technology financing. These businesses can harness digital technology and development programs linked to carbon markets to close existing financing gaps (Michaelowa et al., 2021).

In sum, the cross-sectoral synergies are: 1) a comprehensive environmental tax reform; 2) an SLCP action plan to design instruments focused on emissions monitoring, international cooperation, investment identification, and training the private sector; 3) overhauling urban/municipal regulatory plans to integrate public transport, freight, and waste management; 4) strengthening institutions to oversee the instruments; 5) vigorously promoting low-carbon investment through banks and insurance firms.

4. Discussion and conclusions

We estimated the short-lived climate pollutant mitigation potential per sector and evaluated possible instruments for its advancement in Costa Rica. We focused on black carbon and methane emissions, which contribute to global warming and negatively impact air quality (Stohl et al., 2015). Public policy efforts should focus on instruments that facilitate mitigation in multiple sectors, i.e., cross-sectoral synergies. We developed a value chain analysis of the transport, solid waste, industry, and AFOLU sectors, considering the instruments in existing plans, the barriers to implementation, and possible instruments (proposed by authors) to overcome them. The value chain analysis facilitates scoring and systematizing instruments to find cross-sectoral synergies.

An example of energy sector synergy is having high shares of renewable electricity coupled with flexible hydrogen production, which can fuel industry and long-haul transport uses (Bødal et al., 2020). An example of a cross-sectoral synergy is overhauling urban/municipal regulatory plans to integrate public transport, freight, and waste management. This action will overcome fragmented urban governance, which weakens the capacity to respond and adapt to crises (Sharifi and Khavarian-Garmsir, 2020), fueled by insulated municipal efforts, incomplete plans without performance indicators, and lack of funding and personnel (Boehnke et al., 2019; Messori et al., 2020). Hence, long-term visioning and integrated governance are solutions to fragmentation, supported by public access to real-time and geo-referenced data (Sharifi and Khavarian-Garmsir, 2020). For instance, leveraging information and communication technology instead of new physical infrastructure can facilitate shared urban mobility systems in developing cities (Rosenzweig and Solecki, 2018).

Even with the acceleration of remote work during the COVID-19 pandemic and a drop in transit levels, the corresponding emission reductions will have negligible impacts on temperature change (Forster et al., 2020). Hence, mitigation action is still crucial. However, technical measures alone will be insufficient to transform industrial systems (Singh and Chudasama, 2021). Costa Rica will need to partner with neighbors to advance complementary instruments: transnational governance, technology push (new products resulting from research and development), market-pull (marketplaces demand a new product), technology transfer and financial flows, carbon price, and carbon markets (Singh and Chudasama, 2021). Moreover, our methane emissions analysis shows the importance of consumer behavior for mitigation, e.g., limiting food waste and reducing pressure on landfills (Roe et al., 2019; Willersinn et al., 2017).

Despite the appeal of public-private partnerships to finance low-carbon technology adoption, they can pose vulnerabilities for countries in the case of climate disasters. In that case, the government would need to compensate the private partner by leveraging fiscal power (Dafermos et al., 2021). Indeed, the availability of financial resources will depend on the investors' assessed risk (Battiston et al., 2021). Hence, countries should consider long-term climate adaptation strategies in their short-term plans for coherent policy (England et al., 2018).

The process of identifying the synergies can help Costa Rica and other countries assess their existing plans and formulate more specific actions to integrate climate, air, and environmental quality goals. For example, in some countries, black carbon mitigation can reconcile the interest of developing countries in cleaner air with the interest of developed nations in climate change mitigation (Grieshop et al., 2009).

A limitation of this work is the absence of a broad participatory process to validate instruments systematically, which would be needed to design them. Hence, future work should validate the instrument analysis through a broader expert participation process. The following research step can be the creation of climate policy integration mechanisms, either normative (e.g., laws), organizational (e.g., resource allocation), procedural (e.g., governance mechanisms), vertical (across jurisdictions), horizontal (across sectors) or combined (Medina Hidalgo et al., 2021). Policy integration can lead to a policy implementation network, highlighting the actor setup necessary for successfully implementing the policy (Wagner et al., 2021). Future work can look into the co-responsibility of actors and the number of ties between actors.

Besides black carbon and methane, other SLCPs are hydrofluorocarbons for refrigerants (Climate and clean air coalition, n.d.-c) and ozone (O3) from sunlight interaction with hydrocarbons (including methane) and nitrogen oxides (Climate & clean air coalition, n.d.-d). Although we did not analyze any of such SLCPs in-depth, Costa Rican agencies have studied the possibility of stimulating a market for natural refrigerants as HFC substitutes (GIZ, 2019). The country also has ratified the Kigali Amendment to the Montreal Protocol, which defines the phasedown schedule for HFCs. Future work should model and assess HFCs to produce more comprehensive mitigation strategies. To this end, future work should examine demand-side measures like diet changes and food waste reduction for methane mitigation.

Funding sources

This research was supported by the Climate and Clean Air Coalition, a global coalition of State and Non-State partners who aim to increase action on Short-Lived Climate Pollutants.

CRediT authorship contribution statement

Luis Victor-Gallardo: Conceptualization, Methodology, Software, Visualization, Writing – original draft. **Jessica Roccard:** Conceptualization, Methodology, Writing – review & editing. **Patricia Campos:** Conceptualization, Methodology, Writing – review & editing. **Christopher S. Malley:** Conceptualization, Methodology, Writing – review & editing. **Elsa N. Lefevre:** Conceptualization, Methodology, Writing – review & editing. **Jairo Quirós-Tortós:** Conceptualization, Methodology, Writing – review & editing, Supervision, Project administration.

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

Data will be made available on request.

Acknowledgments

We thank the expert stakeholders in Costa Rica from the Ministry of Energy and Environment, the Ministry of Planning and Economic Policy, the Ministry of Health, the Ministry of Transport, and the Ministry of Agriculture and Livestock. They participated in meetings to assess the scope of the analysis and the identification of implementation barriers.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2022.134781.

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