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Net-zero deep decarbonization pathways in Latin America: Challenges and opportunities

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ABSTRACT

This synthesis paper presents the objectives, approach and cross-cutting results of the Latin American Deep Decarbonization Pathways project (DDP-LAC). It synthesizes and compares detailed national and sectoral deep decarbonization pathways (DDPs) to 2050 compatible with the Paris Agreement objectives and domestic development priorities in Argentina, Colombia, Costa Rica, Ecuador, Mexico and Peru. The first five countries analysed in detail the energy system and agriculture, forestry and land use (AFOLU) at a high level, while Peru focussed on a detailed analysis of AFOLU given its predominance in its GHG emissions. While economy-wide results were produced, this paper focuses on the electricity, passenger transport, and AFOLU results because of their current emissions, potential to grow, and identification of successful strategies for decarbonization (e.g. switching to clean electricity and other net-zero emissions fuels across the economy; urban planning, mode shifting, and electrification in passenger transport; and intensive sustainable agriculture, assignment of land use rights and their enforcement and afforestation in AFOLU). It also highlights where significant emissions remain in 2050, notably in industry, AFOLU, freight, and oil and gas production, all areas for future research. It derives insights for the design of domestic policy packages and identifies priorities for international cooperation. This

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analysis provides critical information for Long-Term Strategies, Nationally Determined Contributions and Global Stocktaking in the context of the Paris Agreement.

1. Introduction

The Paris Agreement established an objective to hold the increase in the global average temperature “to well below 2 °C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5 °C” (Article 2.1). This requires net-zero global energy and land-use CO_2 emissions by the second half of the century (Article 4.1), specifically by 2050–2070 for 1.5–2 °C [1,2], and probably net-negative emissions thereafter. Deep targets also apply to all the greenhouse gases; CH_4 and black carbon must fall by half or more by 2050, and N_2O by at least a third. The Paris Agreement also highlights that these emission reductions must be implemented “in the context of sustainable development and efforts to eradicate poverty” and “in the light of different national circumstances”. This means net-zero deep decarbonization must be aligned with each nation’s development priorities, i.e. economy wide and sectoral climate policy must be designed to maximize synergies with other objectives such as energy security, clean growth, employment, poverty alleviation, access to energy, local air and water quality, and other goals [3,4]. This also means net-zero deep decarbonization can be reached only through country-specific strategies taking into account national opportunities and challenges.

The core strategies of net-zero deep decarbonization are well known: reduce non-welfare enhancing demand, improve energy and material efficiency, decarbonize energy carriers and material inputs and switch end uses to them, and direct GHG reductions through land use and technical negative emissions processes [5–10]. But the challenge is to define country-driven strategies implementing these broad transformations, in a way consistent with national circumstances.

Net-zero deep decarbonization does not mean every country must reach full GHG neutrality. It does require, however, that each region and sector’s emissions trajectory be guided by the goal of carbon neutrality. Some regions and sectors may not go to zero, but this would imply that other regions and sectors go net-negative to compensate for them. From a scenario design perspective, this means going beyond optimization under a carbon constraint and instead focusing on assessment of maximum feasible action in each sector and identification of key country-driven transformations to achieve these emission reductions or sink enhancements.

We also know that aligning national, regional and sectoral emissions with net-zero deep decarbonization is not only about how much is reduced in the short term, but how deep reductions are enabled for all sectors by mid-century through fundamental transformations to energy and material use in buildings, transport and industry, and use of agricultural, urban, and other lands [3,5,11,12]. In contrast to the historical approach of doing cheaper reductions first, net-zero requires selecting short-term actions that pave the way for the long term technical, institutional and behavioural changes needed for all sectors to go to zero or beyond into negative emissions [13]. This requires taking into account path dependencies, inertia, and lock-in risks related to the time it takes to commercialize new technologies, for them to replace existing stock, to build supply networks for new energy carriers, to develop new buildings and transport infrastructure, to shift land-use patterns, and to shift energy using behaviours. This requires strategic thinking based on a long-term horizon in order to inform short-term decisions aligned with the requirements of these transformations, as per Art 4.19 of the Paris Agreement.

The Deep Decarbonization Pathways (DDP) method [4] articulates a process for designing country-driven visions of these inter-related sectoral transformations, helping guide implementation. The DDP method is based on: backcasting from the net-zero emissions target to the present to articulate short and long-run actions and policies to implement the sectoral transformations; recognition of the inextricable relationship between development and emissions goals to investigate synergies and risks of trade-offs; the need to describe detailed physical transformations for each sector understandable by stakeholders and sectoral experts; and identification of possible pathway bifurcations to design robust strategies in a context of deep uncertainty.

The DDP method was used in the pre-Paris Agreement period for 16 industrialized and emerging countries representing 74% of global energy-related CO_2 emissions to investigate a 50% chance of 2°C pathway based on national as opposed to global modelling [5,6]. This original DDP started mostly with experienced modelling teams, focused primarily on energy supply and combustion emissions,[1] and was envisaged as a “proof of concept” research project without structured country engagement. Every one of the 16 teams approached domestic engagement differently, from treating it as an academic exercise to full engagement with decision makers and affected stakeholders to help change national policy.

The Deep Decarbonization Pathways Project in Latin America and the Caribbean (DDP-LAC) builds on this first experience to investigate how six LAC countries (Argentina, Colombia, Costa Rica, Ecuador, Mexico and Peru) can increase their standard of living and develop while reducing net CO_2 emissions to net-zero by mid to late century, with appropriate reductions for other GHGs. Emissions per capita without waste and AFOLU currently range between 1.6 and 4.5 tonnes CO_2 per capita, while including waste and AFOLU drives the divergences to 2.2–7.6 tonnes CO_2e per capita. In these six countries, the share of emissions from transport (27–70%) are higher than the global average (25%), buildings emissions (3–19%) are below the global average (14%) in most countries, while electricity and industry emissions as a whole are around the global average. There are wide divergences between the emissions from the electricity systems of our LAC countries (from 13 (Costa Rica) to 527 (Mexico) grams CO_2/kWh in 2015), depending on regional access to resources like hydropower.

Compared to the first DDPP project, the DDP-LAC takes a broader approach to four specific goals:

1. The building of energy and emissions models where they did not previously exist to allow the establishment of domestic capacities for analysis of emissions and development goals.
2. The building of a regional modelling community of practice where one did not previously exist, in order to facilitate knowledge sharing across countries and the bottom-up emergence of a regional approach to the deep decarbonization challenge.
3. The formation and modelling of qualitative narrative and quantitative scenario reference cases, Nationally Determined Contributions (NDCs) and Deep Decarbonization Pathways (DDPs), covering the most important emissions sources (See Table 1 & Table 2).
4. Using these capacities, approach and results to conduct a structured and sustained engagement with policymakers and stakeholders for purpose of informing domestic climate policy processes, their Long-Term Strategies (Art 4.19) and eventually revised NDCs (Art 4.3 and 4.9) to the Paris Agreement.

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[1] Only the Indonesian team [33], and to a certain extent the Australian [34] and Brazilian teams [35], did fulsome analyses of agriculture, forestry and land use emissions, commonly referred to as AFOLU.

1.1. Structure of this paper

In this paper we describe the synthetic, cross-cutting results of the DDP-LAC project. Section 2 will describe the Deep Decarbonization Pathways (DDP) method as applied in this Project. Section 3 will begin with an overall description of the DDP transformation in the collective DDP-LAC results, and then discuss the sector by sector transformations. Section 4 will discuss the implications for domestic policy package design and international cooperation. Section 5 concludes.

2. The DDP pathways method as applied in LAC

In pursuit of Goals 1 & 2 above, the building and enhancing of both modelling capacity and an analytical community, the DDP-LAC project was established as an initiative of the *Inter-American Development Bank* (IADB) with support from the *Agence Française de Développement* (AFD) and the *2050 Pathways Platform* (2050pathways.org), and is coordinated by the *Institut du Développement Durable et des Relations Internationales* (IDDRI.org). Institutions from six countries were chosen to participate: the *Escuela Politecnica Nacional* of Ecuador*, Universidad de Costa Rica, Universidad del Pacifico* in Peru*, Universidad de los Andes* and *Universidad di Rosario* in Colombia*, Tempus Analitica* in Mexico*,* and *Fundación Bariloche* in Argentina. Given the level of capability from which most of these teams were starting, as per the goal of the project to establish modelling capacity where it did not yet exist, six institutions were chosen to support the teams: COPPE of the *Universidade Federal do Rio de Janeiro* for the Ecuadorian team, *KTH (The Swedish Royal Institute of Technology)* for the Costa Rican team, the *University of Tennessee* for the Peruvian team, the *University of Maryland Joint Global Change Research Institute (JGCRI)* for the Colombian team, *Evolved Energy* of the US for the Mexican team, and *Centre international de recherche sur l'environnement et le développement* (*CIRED)* of France for the Argentinian team. In aid of goal 2, IADB arranged for four workshops over 2018–2019, facilitated by IDDRI and attended by all the LAC partners and support teams as well as IADB, AFD, and 2050 Pathways representatives. The modelling frameworks built and enhanced by the teams are summarized in Table 3; see the teams' papers in this special issue for details of the modelling frameworks.

The choice of model used in each region came from a combination of the capability to do a 1.5–2 °C compatible DDP for the topics and sectors of interest (e.g. macroeconomic restructuring, transport, electricity or AFOLU) [14] and pre-existing relationships with mentor teams. The Colombian team chose GCAM and its support team because of its capability to explore the nexus between the energy system, AFOLU and water. The Mexican team chose Pathways because of its focus on exploring deep, transformative net-zero decarbonization across all sectors in a North American context. The Ecuadorian model, ELENA, was built from the ground-up using Ecuadorian data, but templated on a Brazilian MESSAGE model, partly due to the large MESSAGE support community and the lead modeller's long relationship with the Brazilian mentor team. The Costs Rican team chose OSeMOSYS partly because of its modular nature, allowing it build on existing electricity modelling capacity. The Argentinian team chose the hybrid CGE IMACLIM because of their desire to explore a DDP involving deep macroeconomic structural change. There was no judgment about the "best" model for a region, instead a pragmatic decision combining scientific relevance of the collaboration given the key policy questions to be addressed and the practicalities of establishing the collaboration given past relationships.

Table 1
Estimated 2015 GHGs: Combustion & industrial process CO_2 (Mt).

Energy Supply & Demand, & Industry Process CO_2									
Country	Pop.	Passenger Trans.	Freight Trans.	Electricity	Res. Buildings	Comm. Buildings (Services)	Industry (Comb. & Process)	Total	CO_2 per capita
World Mean		25%		21%	14%		40%		
Costa Rica	4.8	3.5	1.9	0.2	0.2	0.1	2.0	7.7	1.60
		45%	25%	2%	2%	1%	26%	100%	
Ecuador	16.3	6.9	5.2	8.1	3.2	1.0	14.4	38.8	2.38
		18%	13%	21%	8%	3%	37%	100%	
Colombia	47.0	14.5	14.0	16.9	7.0	1.5	41.3	95.1	2.02
		15%	15%	18%	7%	2%	43%	100%	
Argentina	43.1	29.2	19.5	39.1	26.3	4.7	48.5	167.3	3.88
		17%	12%	23%	16%	3%	29%	100%	
Peru '15 BUR	31.0	15.8		0.0	3.0		28.1	46.9	1.51
		34%		0%	6%		60%	100%	
Mexico	121.0	106.3	35.6	137.6	19.5	5.9	239.0	543.9	4.50
		20%	7%	25%	4%	1%	44%	100%	

Goal 3, the modelling of scenarios to represent "climate policy free" reference cases, the outcome of NDCs, and deep decarbonization pathways was enabled by the model building process of Goal 2. The NDCs were modelled as stated out to 2030. For the DDPs, as per Waisman et al. (2019) [4], each team was asked to prepare a political economy narrative of how their country may eventually reach net-zero emissions from where they are today, formulated in a qualitative or semi-quantitative manner and speaking the language of key stakeholders. Each narrative discussed where emissions come from today, on what end-use or sectoral demands they are based on, and described how each of passenger and freight transport, residential and commercial buildings, industry, agriculture and land use might transform towards achieving the goal of eventual net-zero emissions. They then simulated these narratives in their models to translate them into quantitative indicators.

Key to the process, based mostly on outputs from their models, each of the teams was asked to fill in a common "dashboard" for each of their scenarios, thereby providing a quantitative representation of the "storyline" for each of their narratives above. The 2015–2050 dashboard indicators included country-wide indicators for population, economic structure, energy system emissions, and land use CO_2 flows, and for each of the economic sub-sectors as many of the Kaya identity components as the teams were able to provide: activity, energy efficiency/intensity, structural change, and GHG intensity of energy. Where relevent, emissions of non-CO_2 gases were also requested (CH_4, N_2O, SF_6, etc.). The dashboards also incorporated additional sectoral indicators highlighting the main changes in key measurable drivers describing the physical transformations in personal transport, electricity and AFOLU, which are discussed in later sections. The team narratives, the outcomes in GHG emissions per capita, the driving activity, efficiency and intensity variables, and the sector specific descriptions of physical driver changes all come together to describe the country DDP scenario.

A key design point of the DDP pathways methodology is its iterative nature, supported by two learning processes. On the one hand, the dashboard results could be compared by the country teams against initial benchmark national and sectoral emission drivers compatible with the collective climate objective. These benchmarks, derived from the literature, characterize the scale and detail of transformative change required by 2050 to achieve the objective of net-zero emissions in the second half of the century. On the other hand, the common dashboard enables the comparison of assumptions across countries and learning about the possibility of different actions (see Goal 2). These two learning processes led the teams to progressively revise their strategy and scenario assumptions, notably regarding technical potentials for decarbonization in the different sectors. More specifically, at the fourth workshop a seminar was held comparing and contrasting draft economy wide and sectoral DDP results from all the teams. The teams could then see where their results stood compared to the other teams in terms of tonnes per capita and driving variables by sector, and reassess where the differences made sense or not. They then had the opportunity to re-simulate their DDPs. The resulting pathways presented in this synthesis paper and in the country specific team papers of this special issue are the final outcomes of these iterations. They constitute a self-assessment by in-country researchers of what physical sector transformations can be chosen to put the domestic economy on track with the net-zero emissions objective.

In pursuit of goal 4, engagement with policymakers, IADB took the lead in reaching out to local ministries and to introduce the local teams to these ministries if this relationship did not previously exist. The engagement process focussed on establishing awareness of the DDP-LAC's usefulness for informing long-term low carbon development strategies and potentially updating the nations' pre-COP 21 NDCs.

3. Modelling results

3.1. Estimates of nationwide NDCs and DDPs

Fig. 1 combines the DDP-LAC teams' estimates of combined economy-wide combustion and AFOLU CO_2 emissions per capita for both their countries' NDCs as of late 2019 and one of their Deep Decarbonization Pathway (DDP) scenarios. Each team produced between one and four DDP scenarios to represent uncertainties important to their country, as suggested in Waisman et al. (2019), and were asked to select one for cross comparison. The Peruvian team did not provide an NDC forecast for energy combustion emissions. Due to space limitations, we have presented the most ambitious DDP scenario for each team except for Argentina, which discusses their most ambitious pathway in their special issue paper because they wanted to provide more context for it. We encourage the reader to visit the country team papers in this special issue for more discussion of the deep decarbonization strategies and their quantitative results.

A wide body of research has shown that the current global set of NDCs allow too many emissions to meet the 1.5–2 °C goal [15–17], which requires global net-zero CO_2 emissions by 2050-'70 (and gas specific reductions for the other GHGs), and are likely to lead to warming of roughly +3°C. In Latin America it is also the case that the NDCs of major emitter countries are not aligned with the Paris goals [18], and our results support this, with Costa Rica as the notable exception. Fig. 1 shows the NDCs for the country teams that provided them as dotted lines, and the DDPs as continuous lines; most of the NDCs are roughly 1/3 too high to be Paris compatible, unless drastic reductions or very large scale AFOLU or technological negative emissions were employed in later years. All of the Latin American countries' NDCs are subject to ratcheting over the next few years; can these countries use this opportunity to lay out plans to both increase their standard of living and develop while reducing net CO_2 emissions to net-zero by mid to late century? What is involved on a sector by sector basis?

3.1.1. *Development & decoupling: GDP per capita & GHGs per unit GDP*

The individual DDP country narratives were purposefully structured to meet development as well as emissions goals, with reference in the various country narratives to GDP per capita, energy supply security, air and water quality, macroeconomic stability, public welfare, basic education, and for the population to be transitioned from subsistence to formal employment. Most of the countries experience fairly strong economic growth while combustion GHGs per unit GDP fall roughly 80% in most cases (Fig. 2); strong economic growth was predicated in most cases to support development priorities. We refer the reader to the individual country papers for the narratives, but the overall quantitative results support the argument GDP can be largely decoupled from GHG emissions over time in developing country environments. The physical pathways for this are energy efficiency, demand adjustment and restructuring, decarbonization of energy carriers and switching to them, and direct reductions through land use and in some cases biomass with carbon capture and storage; sectoral results are shown in later sections. There is a large difference in the long term growth per capita in the DDPs of the various countries, with the Ecuadorian economy growing 50% per capita by 2050 from 2015 (1.2%/yr), Costa Rica 74% (1.6%/yr), Argentina 93% (1.9%/yr), Mexico 124% (2.3%/yr), Peru 171% (2.9%/yr), and Colombia 177% (2.9%/yr). One alternative Argentinian scenario (while not shown here, it can be found in their special issue paper), based on a return to long run macroeconomic stability, domestically driven growth, and economic restructuring to "upvalue" the economy, showed GDP per capita growing 3.7%/yr to equivalence with 2050 low European levels, assuming continued historic growth rates in Europe. There was some debate between the teams on the utility of "conservative" versus "ambitious" narratives. The former reflects macroeconomic

Table 2
Estimated waste, agriculture, LULUCF and Total GHGs (CO_2e).

Waste, Agriculture, Forest and Land Use GHGs							
	Waste (CH_4)	Agriculture (N_2O & CH_4)	LULUCF mainly CO2	Total non-combustion GHG emissions	Total GHG emissions	Total non-CO2 GHGs/ capita	Total GHG/ capita
Costa Rica	1.9	3.5	−2.4	3.0	10.7	0.6	2.22
	17%	33%	−22%				
Ecuador	2.2	14.3	33.9	16.5	55.2	1.0	3.39
	4%	26%	61%				
Colombia	9.5	45.2	69.0**	123.7	218.9	2.6	4.66
	2.74387	18%	54%				
Argentina	14.9	93.4	50.6	158.9	326.2	3.7	7.57
	5%	29%	16%				
Peru '15 BUR	7.7	19.0	93.0	119.7	166.5	3.9	5.37
	5%	11%	56%				
Mexico	45.9	94.0	−140.0*	−9.1	534.8	−0.1	4.42
	8%	17%	−26%				

*Includes standing forest LULUCF absorptions, as opposed to just managed lands. Each team chose what AFOLU emissions to report, with the condition of transparency what they reported. ** Includes team estimates of illegal deforestation associated with the end of the Colombian FARC insurrection.

Table 3
Model types used by DDP-LAC teams.

	Model name or family	Model type	Includes energy system?	Includes AFOLU?	Includes global linkages?
Colombia	GCAM	Integrated assessment, multiple market partial equilibrium	Yes	Yes	Yes. Colombia's emissions were set within global 1.5 and 2C emissions runs from GCAM.
Mexico	Pathways	Simulation	Yes	Sometimes	No
Peru	POLYSYS	Partial equilibrium	No, other modelling results used	Yes, primary focus	No
Ecuador	MESSAGE "ELENA"	Integrated assessment, optimization, partial equilibrium	Yes	Yes, dynamically balanced with the energy system: demands for useful energy and food and forest deforestation and reforestation scenarios are exogenously calculated	No, but elements can be incorporated from the Brazilian COFFEE model, such as the 1.5 °C carbon budget that was used.
Costa Rica	OSeMOSYS	Energy System Optimization Model	Yes	Added outside model for this project. The team is expanding the model to capture the synergies of the energy sector with climate, land, and water to produce the CLEW model	No
Argentina	IMACLIM & LEAP	Hybrid CGE/Simulation	Yes	Added outside model	Non-energy imports to production share and exports elastic to the terms of trade. Global growth trend for non-energy exports. Exogenous energy trade from LEAP

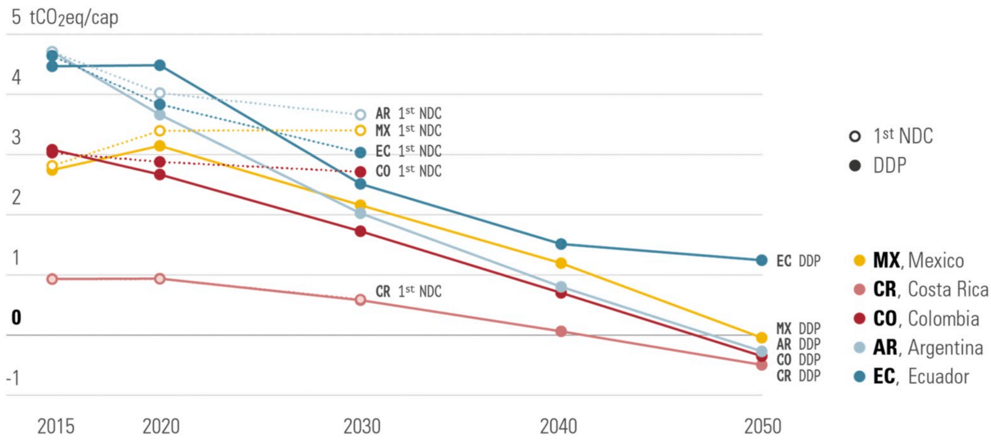

Fig. 1. Projected combustion and AFOLU NDC and DDP CO_2 emissions per capita (tCO_2/cap), excluding other GHGs

reality in LAC today, represented by the Ecuadorian scenario, while the latter would reflect LAC after a generation of political and macroeconomic stability and consequent fast growth in productivity, represented most strongly by the Colombian and Peruvian scenarios. In all cases, however, decoupling of GHGs from GDP is demonstrated.

3.1.2. *Sectoral results*

The DDP-LAC teams produced detailed results for passenger and freight transport, residential and commercial buildings, light and heavy industry, electric power generation, liquid fuel supply and agriculture, forestry and land use GHG fluxes. For reasons of space and because of the predominance of these emissions in an NDC and DDP world, we focus here on electricity, passenger transport and AFOLU.

3.1.2.1. Electricity. Common amongst all the DDPs for all our country team pathways was an economy wide move to electrification of buildings, vehicles and industry combined with decarbonization of electricity production (Fig. 3). Electricity as a portion of final end-use rose from 15-26% in 2015 to 28–82% by 2050; the differences rest on the relative use of electricity to replace liquid fuels for passenger and freight transport. Electricity generation increased 182–428% by 2050 to meet development needs and to allow the transport, buildings and industrial sectors to decarbonize by electrifying. Ecuador, Argentina, and Costa Rica increased electricity output 182–227%. In contrast Mexico and Colombia increased electricity output 425–428%; there was broader and deeper electrification in the latter two countries, mainly from increased use in freight and industry, both directly and as synthetic electro-fuels. Costa Rica reaches the highest rate of electrification, but from the highest starting point. At the same time GHG intensity of electricity falls strongly, from an average 405 to 7 g CO_2/kwh across the region. Every country, however, achieved this reduction differently (Fig. 4), with different mixes of wind, solar, hydro, fossil fuels with CCS, biomass with CCS in Ecuador and Colombia, and nuclear in the case of Argentina, which has a small domestic nuclear industry already. Notably, each region is assumed to have relatively inexpensive access to low CO_2 intensity firm power resources (e.g. hydro, biomass, fossil or biomass fuels with CCS, nuclear), to support high variable renewables penetration at a relatively low cost per kWh [19].

3.1.2.2. Passenger transport. A comparison of passenger transport emissions per capita highlight that the DDPs of Mexico, Costa Rica, Columbia, Argentina and Peru successfully implement decarbonization, while the DDP of Ecuador shows transport emissions initially falling by half and then starting to increase from 2040 (See Fig. 5). The Ecuadorian team noted this was because transport demand per capita increases faster than GHG intensity reductions in the DDP scenario used for the comparison, highlighting the need for international cooperation to reset global passenger transportation technology to zero end-use emissions through electrification or hydrogen fuel cells as fast as possible.

Fig. 6 decomposes the changes in an integrated way using an LMDI

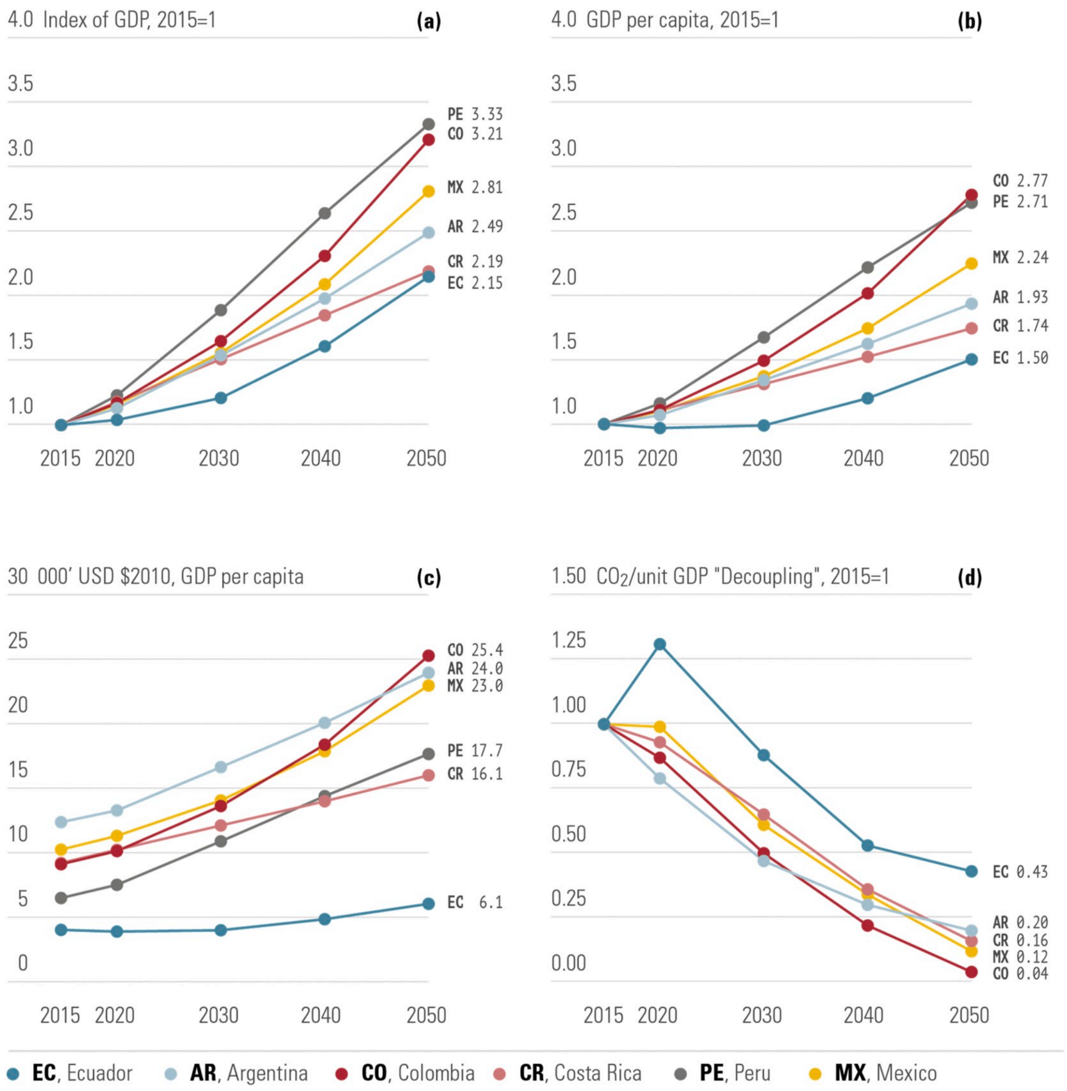

Fig. 2. Index of GDP (2015 = 1) (a) and GDP per capita (b), USD $2010 per capita (c) and index of combustion CO_2/unit GDP (2015 = 1) (d).

decomposition [20,21] (See LMDI Methodology Appendix) of the effects of population, passenger kilometres travelled per capita, energy efficiency, and fuel GHG intensity. As expected, population always increases emissions (−15% of total changes in emissions), as does pkm/capita (−24%"). Energy efficiency improvements always reduce emissions (60%"), as does fuel GHG intensity (78%").

In order to form policy to reduce emissions in the passenger transport sector, or any sector for that matter, the key drivers must be isolated and directly addressed. Total GHG emissions in passenger transport are a function of distance travelled, the vehicle occupancy rate, how efficient the vehicle is, and the fuel used, all of which are affected by mode choices.

The motorized distance travelled per capita increases in most of the DDP scenarios, but at different rates (See Fig. 7). Countries like Colombia and Ecuador with a low-starting value in 2015 experience large increases of 89% and 140% by 2050, while countries like Costa Rica and Argentina with a high-starting value in 2015 experience a moderate growth of 49%–59% by 2050. The Mexican DDP demonstrated a slower growth of 21%, while the Ecuadorian DDP showed a reduction of 10% by 2050 compared to 2015. In spite of their slower growth, Mexico still reaches the highest motorized distance travelled per capita (13 753 pkm), while Ecuador demonstrates the smallest level at 5170 pkm.

However, the role of motorized individual mobility (done by car or two-wheel vehicle) changes in the various DDPs; see the second panel in Fig. 7. The results from four DDPs, including Mexico, Ecuador, Costa Rica and Colombia, indicate that the reduction of the modal share of cars and two-wheel vehicles in favour of more collective transport is a key pathway towards deep decarbonization. In Costa Rica, the share of motorized individual mobility decreases from 70% in 2015 to 50% in 2050. The DDPs for the other three countries show the modal share of cars and 2 wheelers falling from 35 to 55% in 2015 to 25% in 2050. The above transformations are the result of structural changes in urban areas driven by land-use and urban planning strategies to reduce distances and time between human activities, the development of efficient, affordable, safe and comfortable public transport, and behavioural changes towards local activities and tele-activities. In contrast, in Peru and Argentina, the place of motorized individual mobility is estimated to increase to 52% and 70% of their national total mobility. This is due to a large increase of two-wheel mobility in Peru (+400%) and a large increase of car mobility in Argentina (+170%). In these cases, as for all remaining vehicle kilometres travelled, eventual fuel switching to electric, hydrogen, biofuels, or net zero synthetic hydrocarbon fuels would be mandatory.

Total energy use per capita in passenger transport falls considerably in all the DDPs from 2015 to 2050, despite large improvements in living standards. Passenger transport energy use per capita falls -14% in Peru, -29% in Colombia, -30% in Ecuador, -50% in Argentina, -56% in Mexico, and 62% in Costa Rica. It falls the most when the share of electricity used

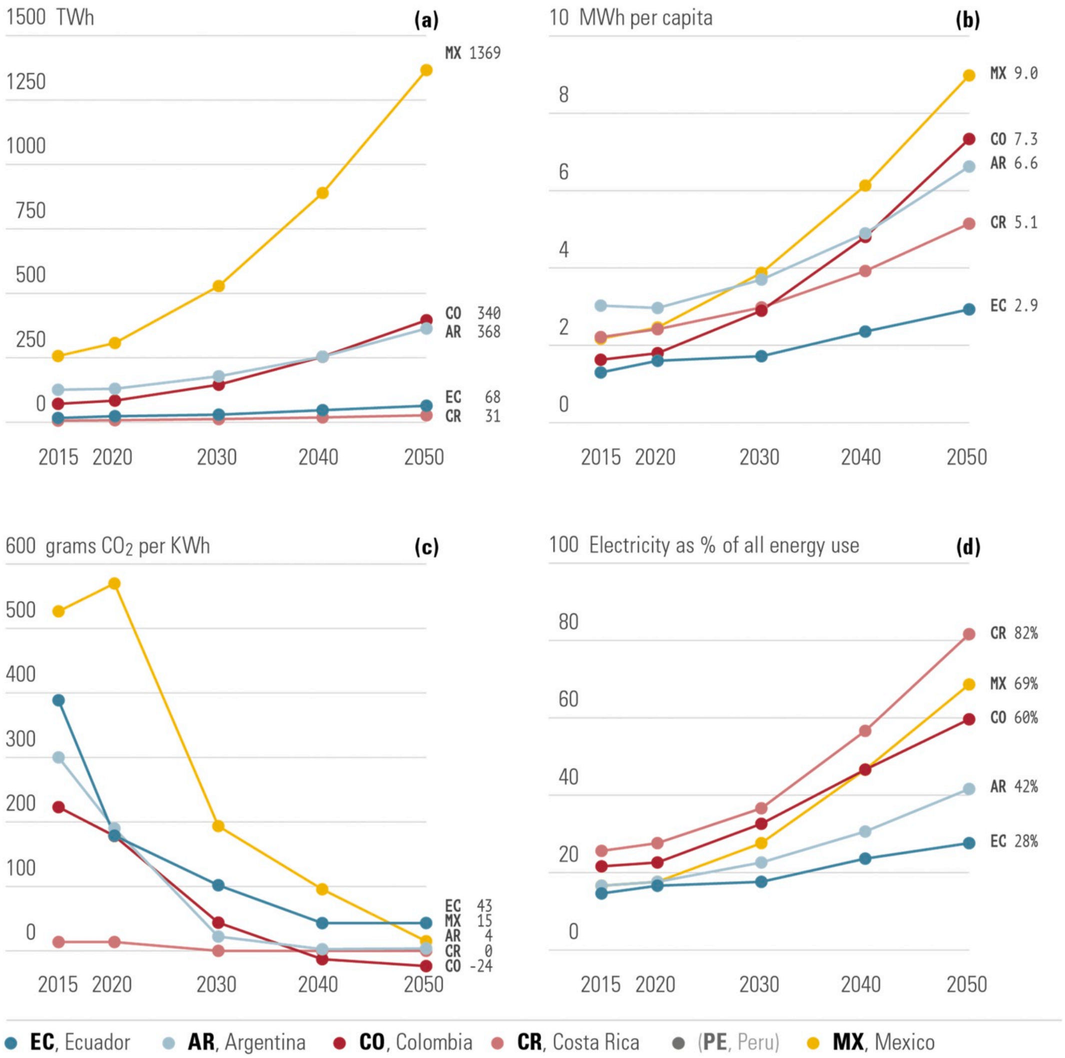

Fig. 3. Total electricity generation in TWh (a), MWh per capita (2015 = 1) (b), GHG intensity in grams CO_2/kWh (c), as % of all final energy use (d).

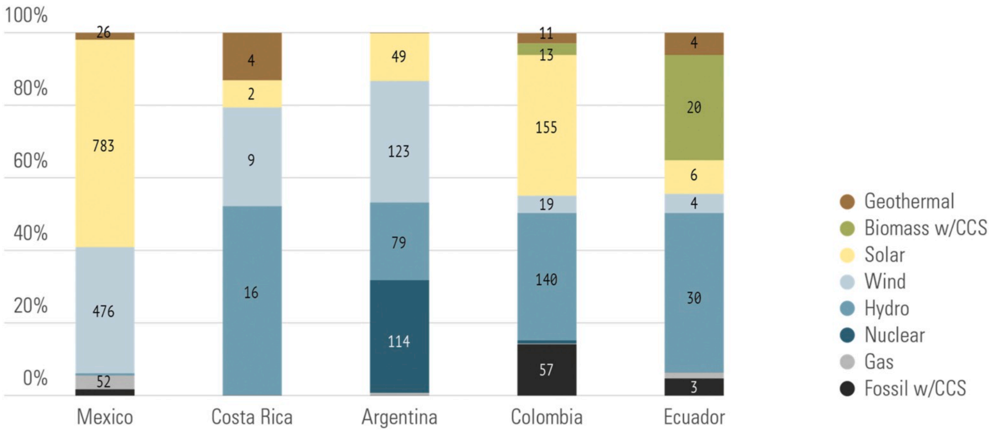

Fig. 4. Electricity generation mix by country in 2050 (Absolute TWh & % of generation by country).

in final energy consumption is the highest; electrification of vehicles inherently improves their end use (GJ per km) energy intensity. Electrification of final transport energy consumption reaches 6% in Ecuador, 21% in Colombia, 43% in Peru, 53% in Argentina, 66% in Mexico, and 100% in Costa Rica. These differences in results do not necessariy reflect fundamental differences about the countries or modelling methods, but assumptions about cost and availability of various low emissions technologies. While all the countries adopt some level of mode shifting to urban electric buses, there are widely varying results for personal cars and intercity transport. (Fig. 8). This underscores the need to reset international standards and resulting economies of mass production for passenger vehicle technologies to ultra-low emissions levels (i.e. battery

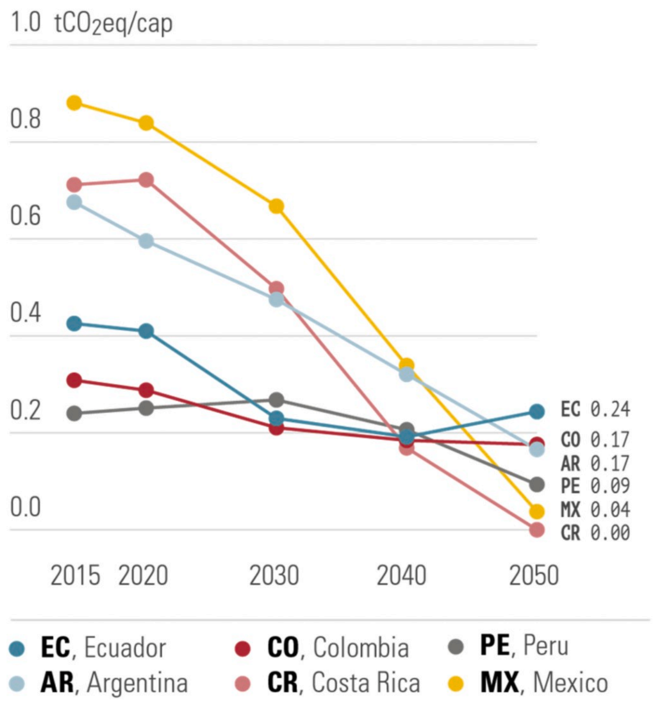

Fig. 5. Per capita transport emissions.

electric or hydrogen fuel cell). These technologies have the co-benefit over biofuels of having zero local air pollutant emissions.

In Fig. 9 we look at efficiency improvements and fuel GHG intensity. Energy efficiency improves 41–75% across all the countries; Ecuador returns to lower fuel efficiency in later years as an optimization outcome from accelerated growth allowed by AFOLU negative emissions (see later discussion). Fuel GHG intensity (not including electricity) varies between −18% to -99% across the regions, with almost all the countries assessed approaching fuel decarbonization differently.

Other specific transformations could be highlighted in the different DDPs, like the role of domestic air mobility, or the roles of liquid biofuels and natural gas. In Ecuador and Peru for example, domestic air mobility represents respectively 10% and 11% of total motorized passenger kilometres in 2050, but 35% and 47% of the total energy consumption of the sector. The Peruvian team estimates biokerosene could eventually replace up to 30% of the aviation liquid fuel requirements, while no aviation biofuels are considered in Ecuador. In Colombia, the consumption of liquid biofuels reaches 29% of final transport energy consumption by 2050; in Argentina, it reaches up to 11% by 2040 before falling to 4% by 2050, being replaced by electrification. In Columbia, this biofuel demand represents 49 PJ of consumption; it would be a significant challenge to ensure sufficient, sustainable production of biofuels for transport and transformation of the land and agriculture sector. Fossil natural gas plays a big role in both Ecuador's DDP and some of Argentina's DDP scenarios, representing respectively about 49% and 22% of the total energy consumption of the sector, yet biogas is not considered. There is considerable scope for wider consideration of lower carbon energy carriers by some of the teams in future work.

3.1.2.3. Other sectors: residences, commercial services, freight transport. We repeat the decomposition exercise for residential buildings (Fig. 10), commercial services (Fig. 11), and freight transport (Fig. 12). Industry is not analysed as it was not a priority for the teams in this project, but it is discussed in the following section, "Remaining Emissions in 2050". Where a team did not provide values (e.g. the change in residential m^2 per person in Costa Rica), this is incorporated in the decomposition as no change from 2015 to 2050.

Population growth always raises residential sector emissions going from 2015 to 2050 (+8.7 Mt, or −21% of the total effect on emissions of −42.3 Mt CO_2). Square meters per person (or total households in the case of Argentina) is used as the structure variable and also always increases emisisons (+5.6 Mt, 13% "). Energy efficiency (−5.5 Mt, 13% ") has variable effects, decreasing emissions in Costa Rica, Mexico and Argentina, and raising it in Colombia and Ecuador. GHG intensity falls across all countries, mainly due to fuel switching to electricity (−51.2 Mt, 121%). There are mixed emission dynamics in Costa Rica, Colombia, Ecuador and Peru due to an ongoing shift from GHG neutral biomass cooking and heating to the use of LPG, NG and electricity. This shift has strong indoor air health benefits associated with reduced indoor particulate matter, but counts as increased GHG emissions to the degree LPG or natural gas is used. In the main, reduced the GHG intensity of fuels used (e.g. electrification or switching to low carbon liquids and gases) has the largest decarbonization effect.

Sector GDP growth (the activity variable) universally increases service sector emissions (+16.3 Mt, −265% of the total effect on emissions, −6.2 Mt). A structure term was not employed. Energy efficiency mostly decreases emissions (−3.7 Mt, 60%). GHG intensity, primarily due to a switch to electricity from refined petroleum products or natural gas, always reduced emissions (−16.2 Mt, 262%). As for the residential sector, energy carrier switching (electrification and switching to low carbon liquids and gases) has the largest decarbonization effect.

The freight sector showed a wide variety of responses from the teams. Sector GDP is used as the activity variable and always increases emisisons (+30.6 Mt, −97% of the total effect on sector emissions).

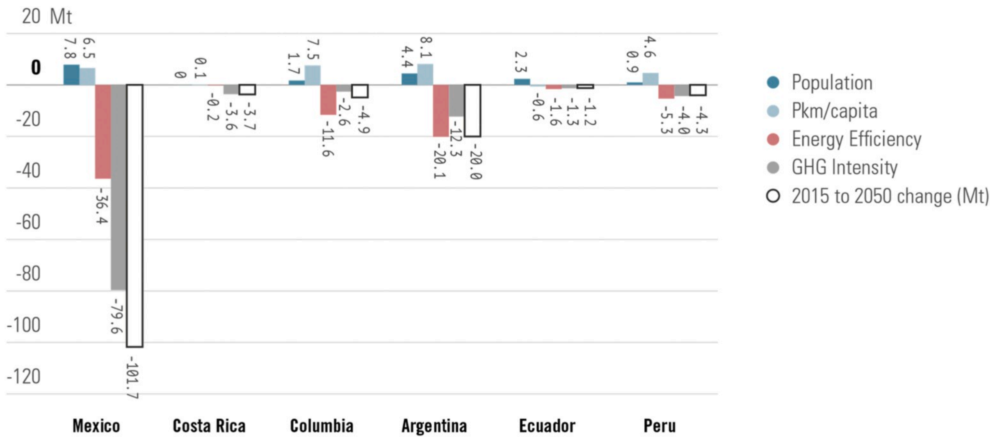

Fig. 6. Changes in Mt CO_2 per year in 2050 compared to 2015 in passenger transport emissions due to population, pkm/capita, energy efficiency and end-use fuel GHG intensity.

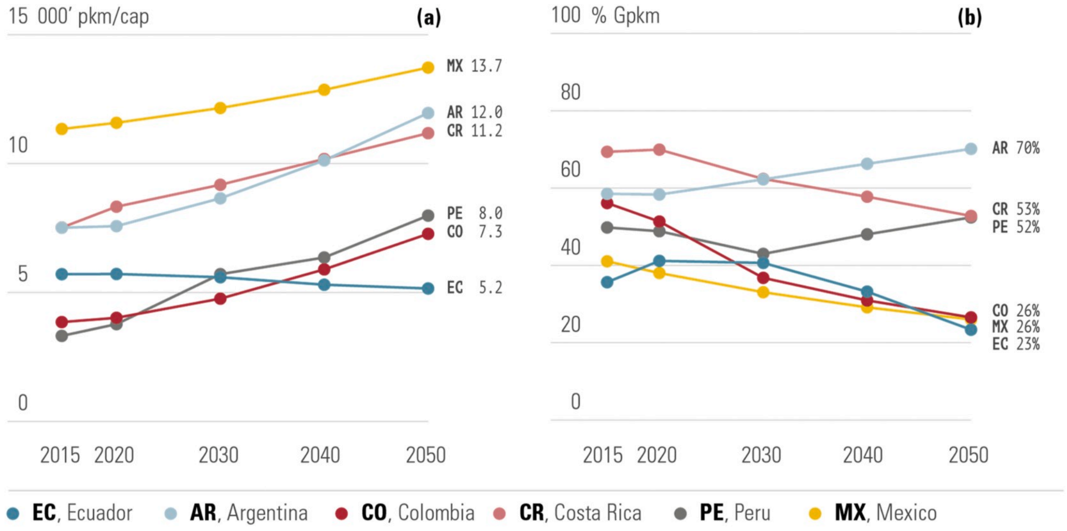

Fig. 7. Motorized distance travelled per capita (pkm/cap) (a) and motorized individual mobility (Car + two-wheel vehicle) share (% Gpkm) (b).

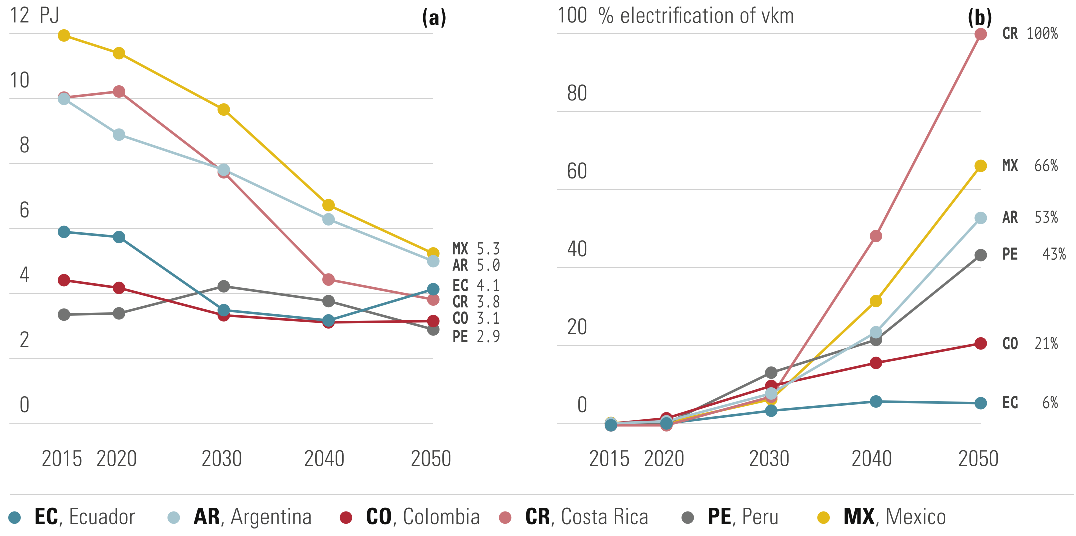

Fig. 8. Total energy consumption for passenger transport (PJ) (a) and electrification of all vkm (%) over time (MJ/pkm, 2015 = 1) (b).

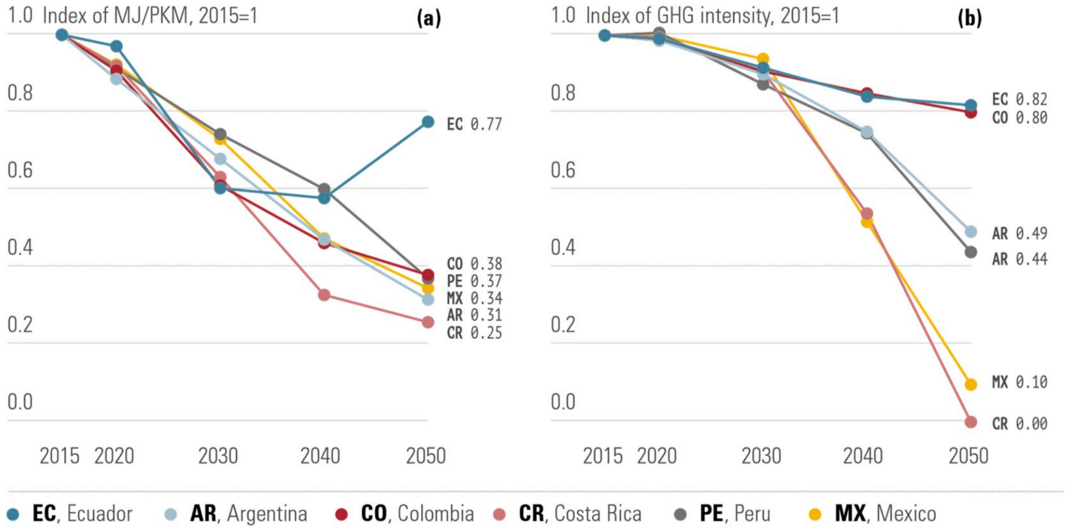

Fig. 9. Passenger transport energy efficiency (a) and overall fuel end use GHG intensity (b).

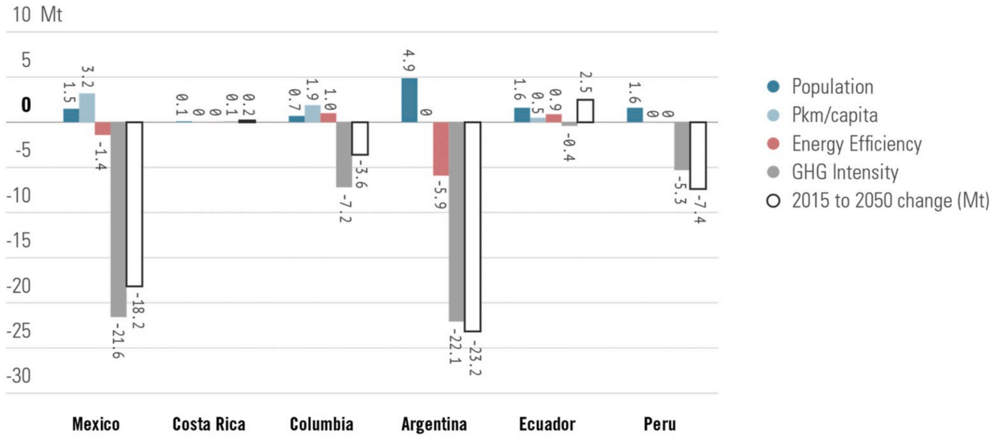

Fig. 10. Changes in Mt CO_2 per year in 2050 compared to 2015 in the residential sector due to population, square meters per person, energy efficiency, and end-use fuel GHG intensity.

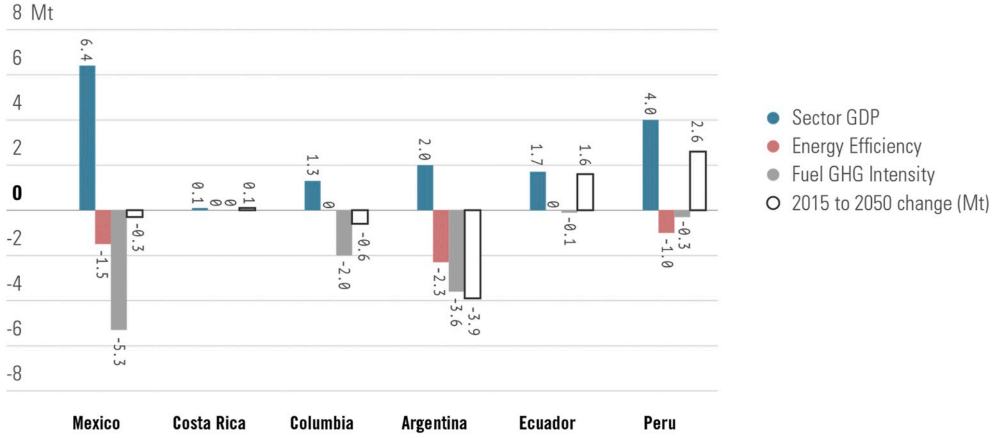

Fig. 11. Changes in tonnes Mt CO_2 per year in 2050 compared to 2015 in the services sector due to GDP, energy efficiency and GHG intensity.

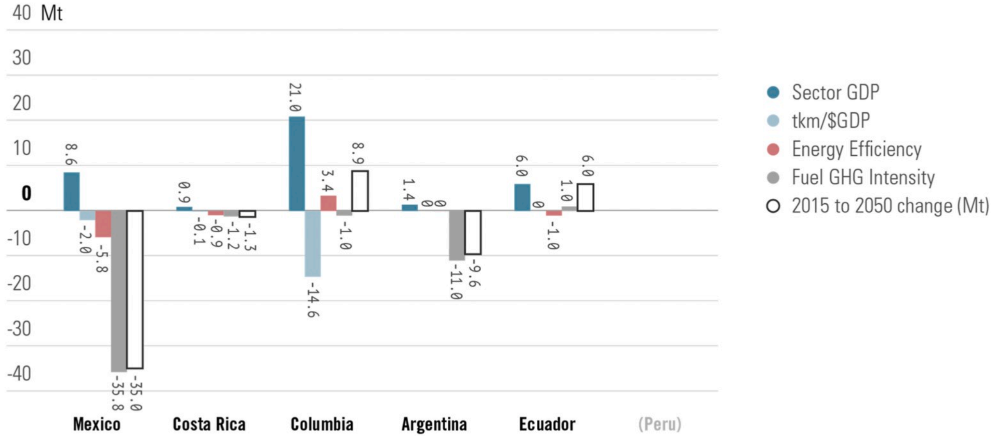

Fig. 12. Changes in Mt CO_2 per year in 2050 compared to 2015 in freight due to overall GDP, tonne kilometres per $GDP, energy efficiency and GHG intensity.

Tonne kilometers per unit national GDP is used as a structure variable, and generally reduces emission (−15 Mt, 48% “). Energy efficiency's effect is variable across countries (+0.6 Mt, 2%). Energy efficiency can improve through direct equipment efficiency and internal mode shifting (which is often used as a structure variable, but the data was not available in this case). Finally, fuel GHG intensity is the predominant effect reducing emissions (−48.6 Mt, 154% “). 80% of this effect is in Mexico, where fuel intensity falls to zero by 2050 based on a moderate modal shift to electric trains and some fuel cell electric trucks. Residual liquid fuel consumption (approx 25% of 2010) is substituted with biofuels and power to synthetic fuels.

A common finding across all three above sectors is the importance of fuel switching to low GHG energy carriers, i.e. electrification and switching to low emission liquids and gases. While national transmission

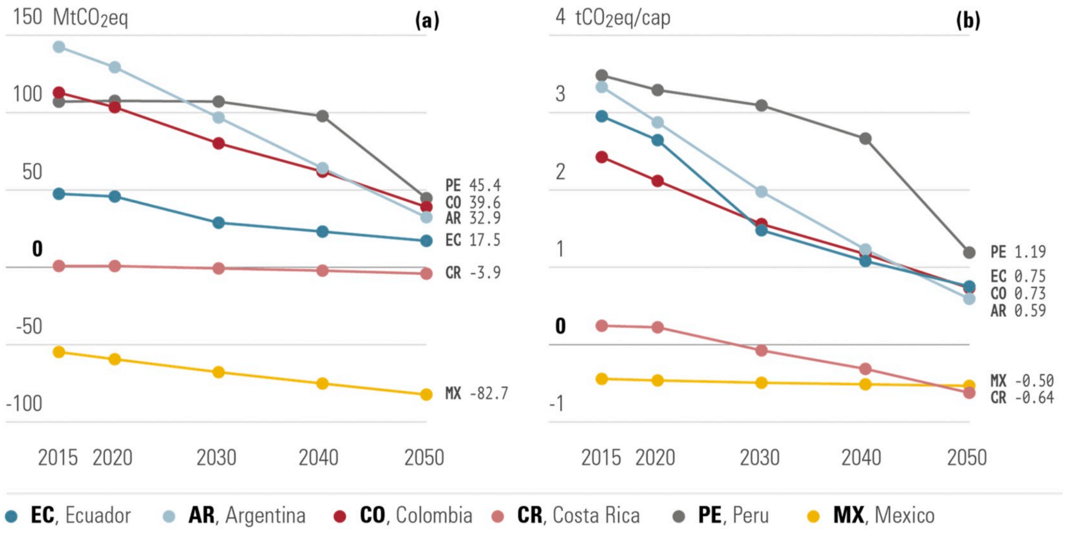

Fig. 13. Agriculture, forestry and land use change emission: absolute (Mt CO_2e) (a) and tonnes CO_2e per capita (b).

and fuel networks will be required, in many cases these are globally manufactured end-use technologies with common global standards, and international cooperation will be required for these physical transformations to occur and be affordable in a developing country context.

3.2. *AFOLU carbon flows*

Decarbonising the AFOLU sector by 2050 will be a challenge given a growing demand for food and increasing or maintaining agricultural exports in most of our LAC countries. All six countries included in this study project AFOLU emissions trajectories that decline from 2015 to 2050; note that AFOLU includes FOLU CO_2 and mainly agricultural CH_4 and N_2O. Fig. 13 provides absolute and per capita AFOLU emissions. Mexico is the only country to have net negative emissions in 2015, based on inclusion of net carbon flows into previously degraded forestry and agricultural lands (−55 Mt/yr in 2015), with the negative flux increasing to −83 Mt/yr by 2050. Costa Rica's emissions decline the most over the period, by 436%, and they reach negative emissions between 2020 and 2030. Costa Rica has a long track history of progress in this area, having returned forest cover from 26% in 1983 to 52% today. As for Argentina, Colombia, Ecuador, and Peru, their emissions fall significantly (between 58% in the case of Peru and 77% in the case of Argentina), and all have net positive emissions from the AFOLU sector in 2050. This section will proceed by analysing emissions from land use change and emissions from agriculture separately.

In terms of AFOLU emissions per capita, which makes cross country comparisons possible, all countries have decreasing per capita emissions, with reductions ranging from 0.09 tonnes/capita for Mexico to 3.04 tonnes/capita for Argentina. Peru has the highest per capita emissions throughout the period, going from 3.49 to 1.19 tonnes of GHG emissions per person. Costa Rica, which has the smallest population, have the lowest emissions in 2050, at −0.64 tonnes of GHG emissions per person.

3.2.1. *Land use change*

Regarding land use change (LUC) emissions (Fig. 14), which is denominated in CO_2, Mexico and Costa Rica are net sinks in 2015, whereas in 2050, Argentina, Colombia and Ecuador also evolve to having net negative emissions. Mexico stands out as the largest net sink, and sequesters roughly 171 $MtCO_2$ annually in 2050, while Argentina's annual emissions reduce the most over the period (by 140 $MtCO_2$). When interpreting these results one should bear in mind that the Mexican team has included the large annual sink from natural regrowth in previously agricultural or degraded lands. In their paper they include specific discussion of the need to preserve and enhance these sinks, which could potentially make them count as "managed lands" under UNFCC accounting rules.

Forest deforestation and afforestation (and growth in previously deforested post-agricultural lands in Mexico) are the major negative and positive drivers of land use change GHG emissions. The other land types play a relatively small role because none of the teams included soil carbon, the primary means by which other land types sequester carbon. Forests sequester carbon through the natural growth process of trees and other plants. By the same measure, if the amount of biomass in the forest falls because of wood harvesting, burning, or natural decomposition of dead trees, the forest releases the carbon back into the atmosphere. There are three subcategories of forest emissions (including negative emissions) that occur in the country scenarios: forestland gains, which comprises both afforestation (when land not previously under forest cover becomes forested) and reforestation (when land previously under forest cover becomes forested); forestland loss (deforestation); and forestland remaining forestland (which either gain or lose carbon stocked in biomass). Increased annual sequestration in already existing forests explain the lion's share in both Argentina's and Mexico's negative emissions from LUC. Afforestation or reforestation is also an important contributor to negative emissions in Argentina, Mexico and Peru. The latter, however, has positive emissions from deforestation that overwhelm the negative ones from afforestation or reforestation. Ecuador and Peru are the only countries to project some deforestation, while the other four either do not have information or project zero deforestation. Emissions from deforestation have ceased by 2035 in the case of Ecuador while they remain static for Peru.

In Argentina, Ecuador and Mexico, the surface of forestland expands, by 1–4% of the national surface. In all three cases, the prior land use of the afforested or reforested land was primarily grassland used for grazing animals. In Peru and Costa Rica, the forest cover remains static, although there are changes in the cover of other land use types.

The Peruvian special issue paper is one of the few to articulate a policy package to reduce deforestation, increased afforestation and otherwise reduce agriculture emissions. The policy package rests on the idea that forest decarbonization interventions need to induce stakeholders to value the sustainable use and conservation of an ecosystem that took centuries to develop. It rests on five pillars: sustainable forest management; commercial reforestation; rights allocation and enforcement, especially for indigenous populations and sustenance farmers; broad incentives and aid to native communities; and management aid to natural protected areas. The Peruvian policy package also includes measures to increase product diversification, enhance the ongoing

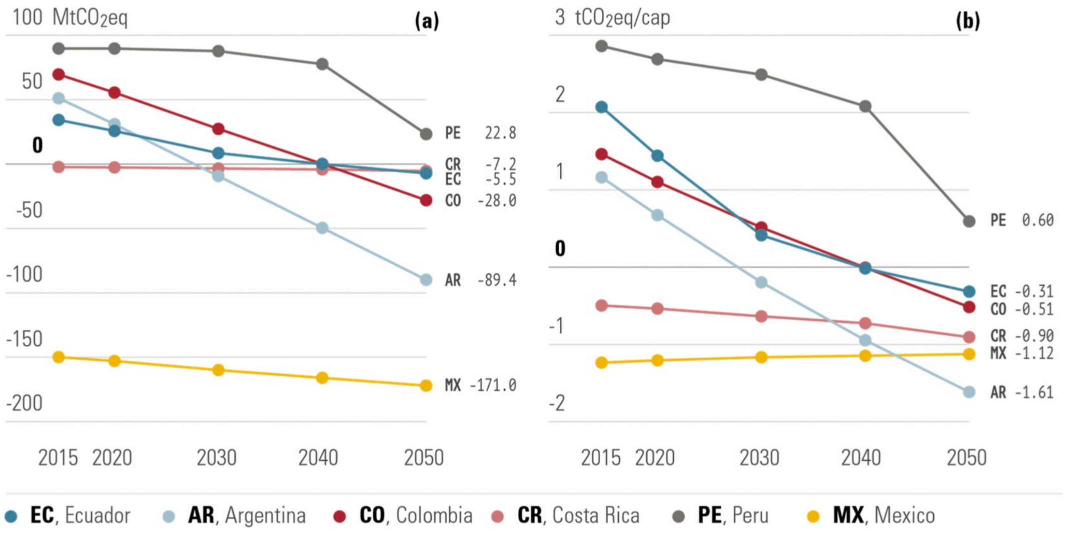

Fig. 14. Land use change emissions by country: absolute (Mt CO_2) (a) & per capita (tonnes CO_2 per person) (b), excluding all non CO_2 GHGs.

process of moving to higher value products, reduce fertilizer intensity, and to introduce dry periods for rice lands to reduce methane formation. Finally, it suggests the use commercial afforestation, especially to buffer old growth Amazonian forests – this is discussed in more detail in later sections.

There are some important accounting differences among the countries, which complicates a straightforward comparison. For instance, Argentina and Mexico are the only two countries to account from sequestration in forestland remaining forestland, and this emissions category plays an important role for the total emissions in both of these countries. Colombia, Costa Rica, Ecuador and Peru do not account for this category of negative emissions, which could contribute to explaining the lower negative emissions from those four countries. Another potential difference is the scope of the forest-related emissions taken into account. Peru and Costa Rica are the only countries that take into account sequestration from secondary forests and permanent crops/plantations, while projecting the area of primary forests to remain the same. Future analyses could focus on greater reporting consistency, but there are significant political issues associated with land use emissions inventory reporting, e.g. what fluxes can and should countries count and be held accountable for?

3.2.2. *Agriculture*

All our LAC countries face a growing population (16–29%). Growing populations and maintained or increased agricultural exports put a strain on the agricultural sector, which must substantially increase its production to maintain a similar level of food security, lest the country increase its imports of food products or reduce its exports. In some countries, a significant part of the agricultural production is destined for exports, often an important source of income and employment.

Total agricultural emissions for each of the DDPs is provided in Fig. 15, and is composed of varying mixtures of CH_4 from enteric fermentation, N_2O decay from synthetic fertilizers, CH_4 from rice paddies, and a combination of emissions from other land management practises. Colombia (+50%), Argentina (+31%), Ecuador (+73%) and Peru (+17%) increase their total emissions over the period, while Costa Rica (−53%) and Mexico (−6%) decrease their emissions.

The major source of agricultural emissions in all countries included in this study is methane from enteric fermentation, which arises from the digestion of fibres in ruminant livestock, primarily cattle. Nitrogen oxide emissions from synthetic fertiliser application also play a key role in many of the countries. Emissions from fertiliser application tend to increase more than emissions from enteric fermentation (EF) in the countries' scenarios. In the case of both Mexico and Argentina emissions from fertilisers increase while those from EF decrease. For Ecuador and Colombia, emissions from fertilisers increase much more than emissions from EF as both sources of emissions increase. Peru, where emissions from fertilisers stagnate whereas emissions from EF increase, is the exception to this tendency. This indicates that in order to reduce AFOLU emissions, emissions from animal production are easier to mitigate than emissions from vegetal production. A parallel tendency in the scenarios of the countries is that livestock herds in most cases remain static, or at least grow by a lower percentage than fertiliser usage, which increases strongly for all countries. More research is required for all the above to ascertain deep decarbonization pathways for agriculture.

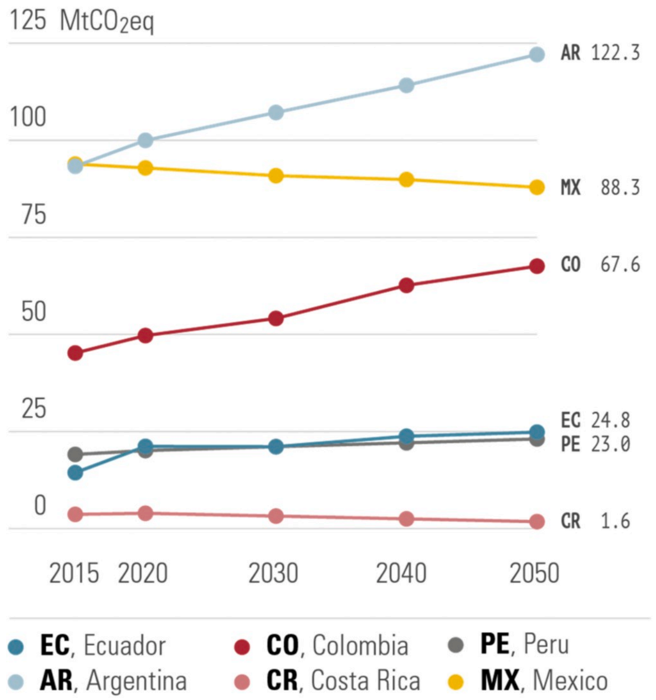

Fig. 15. Agricultural emissions, CH_4 and N_2O ($MtCO_2e$).

3.2.3. *Further AFOLU analysis*

Putting agricultural emissions in relation to the total production provides another perspective, providing an indication of the sector's capacity to decarbonize while feeding a growing population and maintaining exports. All our LAC countries increase their food production and most of them substantially. Argentina increase theirs the most, and increase crop production by 63% (in tonnes) and animal herds by 46% (in Livestock Units), much of which is exported. Costa Rica has the lowest increases, an 9% increase in crop production and 2% in livestock herds. Importantly, five of the six countries also manage to decrease their emissions per unit of output (both per tonne of crop yields and per livestock unit) – Costa Rica by over 400% (which is possible as their emissions go net negative). The only exception to this is Mexico, which increases its emissions per unit of output.

The increase in agricultural production can in all cases be explained by an intensification of agriculture (i.e. increases in output per unit of land). This intensification is on the one hand illustrated by increases in the yields and increases in the livestock density. All countries except Costa Rica increase their yields drastically, ranging from 43% in the case of Peru to 68% in the case of Ecuador. The livestock density remains static for Mexico and Ecuador, but increases by 24% for Peru and 70% for Costa Rica. Hence, all countries intensify either vegetal or animal production, and two countries (Peru and Argentina) intensify both. The intensification of vegetal production is sustained by an increase in the application of synthetic fertilisers, which increases in all countries except Peru – and in Mexico it more than doubles. On the other hand, the intensification is illustrated by reductions in total land used for agricultural production, which includes both cropland for vegetal production and grassland for grazing animals and production of fodder. Ecuador, Costa Rica and Mexico all decrease the land available for agricultural production, by as much as 17% in the case of Costa Rica. The surface of agricultural lands remain unchanged in Argentina, whereas Peru increases its agricultural land.

By dissecting the AFOLU sector into land use change and agriculture, it is clear that to the extent that countries decarbonize in their scenarios, this is mainly possible through reductions in land use change emissions rather than agricultural emissions (which increase in four out of six countries). One explanation for this could be the growing populations in each country, as discussed above. Another, cited by Argentina, is the capacity to free large tracts of land for afforestation (the same explanation could perhaps be applied to the cases of Ecuador and Mexico, which also afforest or reforest significantly). Interestingly, all countries in this study have chosen to pursue a path that in one way or another intensifies agricultural production, which on the one hand in part relies on emission-intensive activities in agriculture (e.g. fertiliser application), while on the other hand liberates land for afforestation or reforestation and thereby enables emissions reductions. In sum, even with improved agricultural productivity, technology and best sustainable practices, there is a significant trade-off between agriculture, livestocking, forestry, and natural land use sinks.

3.3. *Remaining emissions in 2050*

Fig. 16 indicates the remaining absolute 2050 GHG emissions for each country in the DDP scenarios, which is interesting because it contains both legitimate resistance to mitigation that will require stronger and more creative innovation and policy, and decarbonization pathways as yet unexplored by the teams. Fig. 17 translates this into more comparable tonnes CO_2e per capita. While one must be careful in comparing results from countries with very different national circumstances, several things stand out. First is the widely varying nature of AFOLU emissions, which partly reflects the nature of the natural and human influenced fluxes in each country as well as the level of ambition for reducing emissions from this sector; for some teams (Ecuador and Colombia) the energy supply and demand models optimized including AFOLU, in the others it was modelled separately from the energy system. Second is that emissions have been largely squeezed out of electricity, residential buildings, and services; decarbonization pathways are well known for each of these, e.g. reduced fuel GHG intensity through electrification. Varying levels of emissions remain in passenger and freight transport, depending on the degree of urban planning, mode shifting, and vehicle technological options made available in the DDPs, including widely varying assumptions about the potential for battery electrification, biofuels or hydrogen fuel cells. Substantial emissions remain in light and energy intensive industry, which were not a focus of this project, but merit further attention in the future.

It has been noted in a growing literature that there is a class of "hard(er) to abate" sectors, including freight transport, aviation, steel, cement, chemicals and other heavy industry [8,9,23,24]. These results were repeated in this project as remaining emissions in the country DDPs. Further research could prioritize projection of demand forecasts, likely domestic production, potential material efficiency improvements [25], and how to decarbonize production or end-use services in these sectors [26–29] in the LAC context. Given remnant light industry emissions, given this sector's capacity for electrification, use of waste or solar heat, heat pumps, and replacements for natural gas (e.g. biogas, biomethane or hydrogen), further research is warranted to include these options in the models.

The Colombian and Ecuadorian teams notably used biomass processing and carbon capture and storage to generate negative emissions, while the Ecuadorian team used biomass and carbon capture and storage electricity generation.

A positive outcome from our DDP results are the relatively small remaining oil and gas production and refining emissions. Oil and gas emissions form a large part of current inventories [22] and their

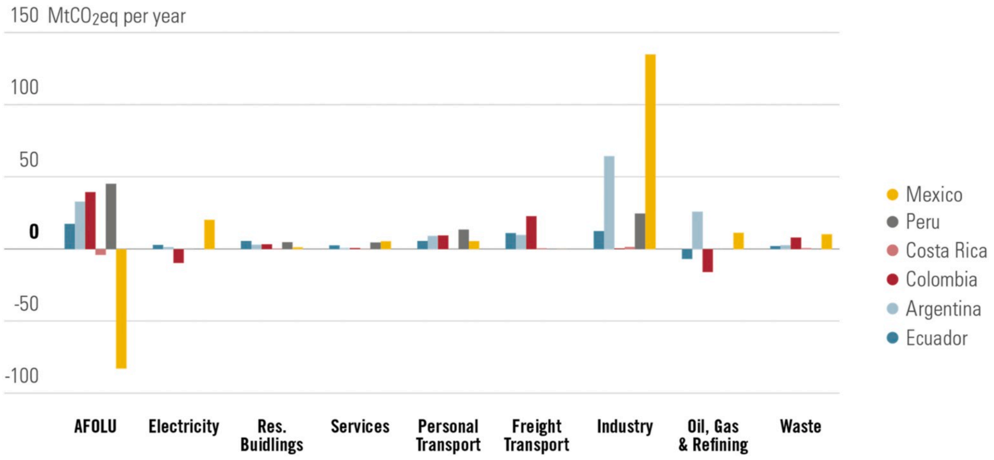

Fig. 16. Remaining 2050 GHG emissions in the country DDPs, including negative fluxes (Mt CO_2e per year).

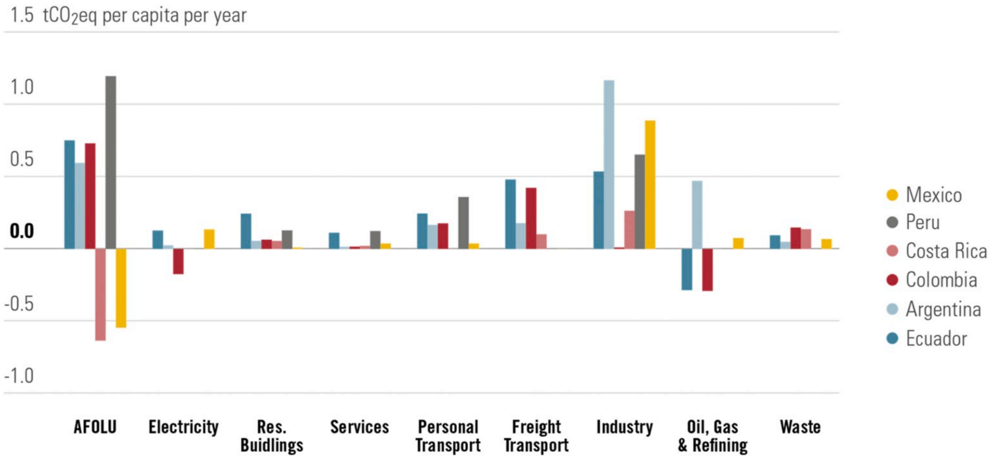

Fig. 17. Remaining 2050 emissions by sector per capita (tonnes CO_2e per capita per year).

relatively small level in the DDPs, which are first analyses for many of our teams, is a welcome development. The scenario used for Argentina has significant gas production from the Vaca Muerta reserves; other scenarios produced by the Argentinian team and discussed in their special issue paper do not. Reduced oil and gas revenues will, however, have fiscal implications for several of our LAC countries.

4. Discussion

4.1. Domestic policy package design and international cooperation

The contrast between the first round NDCs and DDPs shows there is a need for government and stakeholder visioning and planning to allow policy package design to move the long run evolution of our LAC countries off a fossil fuel orientated pathway to one heading towards net-zero later this century. While much of the power and capability to do this sits within these countries, the physical nature of the sectoral transformations outlined in our DDPs have shown there is wide scope for international cooperation to reduce GHG emissions to net-zero levels in Latin America, and in developing countries in general.

4.1.1. Transportation

The passenger transportation results for most DDPs showed a largely successful transformation to low carbon transport met through differing mixes of urban planning, mode shifting enabled by infrastructure and transit construction, electrification of buses and passenger vehicles, and alternative net-zero liquid fuels (e.g. sustainable biodiesel and ethanol). About half the DDPs also dealt successfully with freight through electrification, mode switching and alternatives for fossil diesel.

Very large transport investments are already being planned as the LAC countries urbanize and their populations grow. A key policy initiative will be to shift much of that investment to low and zero emissions higher capacity transport and urban planning, rather than lower occupancy gasoline vehicles. While urban planning and infrastructure construction is under control of the national, state and local governments within their management and financial capabilities, some nations and regions may need assistance doing state of the art, higher density, high transit and non-motorized mobility urban planning and infrastructure building. They may also need assistance with concessional “signalling” or “de-risking” capital to help access private capital markets for capital intensive urban transit, e.g. Peru and Lima in particular may need assistance with planning, construction and finance of the Lima metro, which is planned to displace 4 million passenger vehicles.

Full electrification of new buses and private vehicles will require that these technologies become the new regulated norm for transport use; this will only occur if this is so at the global level given the interlinked nature of global transport manufacturing and the necessary economies of scale to make battery and fuel cell vehicles affordable. While electric buses and cars are probably already cheaper than their fossil counterparts on a life cycle basis, and may eventually be cheaper than gasoline and diesel versions on an upfront basis depending what happens with battery costs, they currently cost more to buy. Policy is needed to address this, non-exclusively including low cost finance for bus fleets, targeted and declining subsidies, GHG intensity performance regulations that match global efforts, and building of charging networks [30]. LAC cities may also need aid with guiding the private sector in planning and implementing electricity charging and alternative fuel networks, both for reasons of equity and making sure all parts of cities and eventually countries are covered. Finally, subsidies for transport fossil fuels will have to be reduced and eventually eliminated as fast as domestic politics allow.

Decarbonization of transport, small and large buildings and light industry requires large amounts of clean electricity in our DDPs, which comes from various mixes of wind, solar, hydro, nuclear and biomass with carbon capture and storage. Increasing clean electricity output by +182–425% as shown in our DDPs will require efficient, low cost procurement, associated transmission and increased domestic installation capability for all parts of the supply chain. Electricity generation and transmission construction will require clear policy direction for both output and GHG intensity. The output signal can be provided by normal electricity planning and market processes combined with stated government intentions and policies to electrify transport, buildings, appliances, and light industry end-uses. The GHG intensity of generation signal can vary, but will likely be provided by strong and effective regulatory and planning structures orientated towards building mainly low and zero GHG generation and associated transmission, e.g. renewable portfolio standards, or simple requirements that all new generation be very low or zero emissions unless for balancing variable renewables. All the above will require efficient market structures that send appropriate marginal and average pricing signals to consumers and provide the means to amortize the invested capital, whether it be by self-generating households, buildings and industry or by conventional power utilities. Our LAC countries may benefit from assistance from regions and utilities globally that have integrated higher (i.e. >10%) levels of wind and solar while maintaining system stability and reliability at a low cost, and how to use existing assets (e.g. impoundment hydroelectric dams) and resources to do this.

Transport and energy infrastructure investment, reduction of oil and gas revenues, and reduced subsidies for fossil fuel use will have significant combined municipal, regional and national impacts on government revenues, and net government financial flows must also be considered as part of the national planning process. Long term tax reform towards incentive structures that encourage innovation, employment, investment, and limitation of GHG emissions while maintaining government revenues to provide public goods will need to be considered in the long run. We did not include this tax reform analysis in DDP-LAC, but encourage exploration of this dynamic in future work.

AFOLU has perhaps the greatest scope for international cooperation that extends beyond current market and finance based development bank channels. All our participating countries exhibit relatively large fluxes from deforestation, afforestation, and agriculture compared to their populations, and very large potentials to turn the positive fluxes down (e.g. reduce deforestation) and increase negative fluxes (e.g. increase afforestation, reduce fertilizer use, extend best practises, diversify current mono-cultures, increase soil carbon sinks, etc.). These fluxes are an outcome of the behaviour of millions of individual, family and firm units, many without security of land tenure or the ability to enforce their tenure and use rights, etc., which leads to very short run orientated decision making (e.g. low productivity slash and burn agriculture). Reducing deforestation, increasing afforestation, and other practises to reduce emissions are also made harder by illegal mining, agriculture, forestry, the end of guerrilla warfare in the case of Colombia (i.e. the civil insurrection paradoxically reduced deforestation by denying access land access to those would deforest), and illegal deforestation for cattle, etc. For example, in Brazil deforestation is mainly the sequential outcome of small sharecroppers pushing their cattle into government forest lands to establish “squatters rights”; once these rights are established, they sell the land to larger agricultural firms [31]. Brazil was successful for many years slowing and halting this process using unarmed or lightly armed police; once these police were removed, the process of deforestation resumed. In Ecuador and Peru, deforestation is the outcome of subsistence farmers with insecure or absent tenure resorting to very low productivity slash and burn agriculture, sped up in Ecuador’s case by oil and gas roadmaking into the Amazon. If the skills of these subsistence farmers could be improved, and better paid work available to them, deforestation would likely slow down. Policies based on establishing and enforcing land tenure (e.g. in Ecuador, Brazil, and Peru) have been successful in the past in reducing deforestation, increasing afforestation, and supporting sustainable efficient agriculture. A careful assessment is needed of how these kinds of policies can be encouraged and supported domestically and internationally, and should be a key focus of future work. Finally, the Peruvian special issue paper noted there is a substantial opportunity, beyond the domestic financial resources of the Peruvian government, for large scale commercial afforestation to induce negative emissions, improve biodiversity, and perhaps most importantly, help stabilize the size of the Amazon at a scale large enough to maintain its unique, self-sustaining hydrological conditions [32].

The IPCC Special Report on 1.5 °C indicates that large, gigatonne scale negative emissions (up to 3.6 GtC per year from land use in 2050, and up to 5.0 GtC per year of biomass with CCS) will be needed from land use and negative emissions technologies, increasing with time [2]. As currently constructed, the international climate policy governance regime provides very little incentive for a country with large carbon fluxes under its management to manage for the global sink. The incentive is very strong to count these fluxes towards the domestic inventory and use them to reduce or slow the need to reduce energy system emissions to net-zero. This has important long-term implications for regions with the capability to go net-negative (e.g. those with significant land use sink potential, such as in Latin America). Do they use it for their own purposes to balance their emissions for growth purposes, or transfer these negative emissions, which will likely be needed for ambitious temperature goals, to a global “fund” within the context of their sovereignty? We do not pretend to offer an answer to this conundrum, but instead provide evidence of the importance of providing a robust and effective incentive structure for LAC countries to assign their negative emissions to the global sink, while lowering their energy system emissions to zero.

4.2. Lessons for future DDP-like processes

First, the teams very much benefitted from co-reviewing of their results at the fourth workshop in Quito after all their model building and scenario construction. A longer, more iterative approach with more co-review opportunities would likely have been beneficial.

Second, this project was initially meant to be only about energy supply and demand, but the predominance of AFOLU in the national inventories of the LAC nations encouraged some reprioritization to a combination of energy supply and demand and AFOLU emissions. This might have been an easier transition if there had been a longer workshop at the beginning to review regional priorities in a Paris compliant world.

Finally, when taken altogether, the cross-country diversity of country strategies illustrates the breadth of options available to decarbonize. Considering more systematically all the different options in each country context will be a priority next step in our research agenda, both to investigate more robust strategies and to explore possibilities for deeper cuts.

5. Conclusion

The DDP-LAC project has shown that pathways can be developed for LAC countries to reach net-zero GHG emissions while benefitting from economic growth, improved air quality, lower cost and higher quality transport, and other benefits. Implementing these pathways will require economy wide and sectoral policy packages designed to evolve as new information is acquired, that address all emissions and development goals, and are sensitive to the regions’ needs and circumstances. The results presented in this paper, detailed at a sectoral level and explicit in the content of physical sectoral transformations, can help provide policy-relevant insights for national discussions about the transition and possibly inform these countries’ Long Term Strategies, revision of their Nationally Determined Contributions to the UNFCCC, and short and long run policy formation.

6. LMDI appendix

Our decomposition analysis starts with an identity that accounts for four generic factors (overall activity, end-use intensity per unit activity, energy intensity per unit end-use, and fuel GHG intensity per unit energy) that influence CO_2 emissions from fossil fuel consumption (Equation (1)) [21].

$$C=\sum\left(Activity\cdot\frac{SectorEU}{Activity}\cdot\frac{Energy}{SectorEU}\cdot\frac{GHG}{Energy}\right)=\sum(A\cdot EU\cdot EE\cdot G) \tag{1}$$

Where:

C = CO_2 emissions
Activity = Activity or sector GDP. We used population in the case of passenger transport and residences (households for Argentina), and GDP for services and freight.
SectorEU = Sectoral end-use demand per unit of overall activity (pkm/pop for passenger transport, sq m^2 per capita for households, tkm/$GDP for freight, none for services)
Energy = Energy consumption by sector end-use demand
GHG = GHG emissions by sector

To compare the CO_2 emissions in 2050 and 2015 in Equation (1):

$$\Delta C=C_{2050}-C_{2015} \tag{2}$$

$$\Delta C=\sum(A\cdot EU\cdot EE\cdot G)_{2050}-\sum(A\cdot EU\cdot EE\cdot G)_{2015} \tag{3}$$

$$\Delta C=\Delta A+\Delta EU+\Delta EE+\Delta G \tag{4}$$

Where:

ΔC = Difference in total CO_2 emissions between region c and region m
$\Delta C_{Activity}$ = Difference due to activity
$\Delta C_{EndUseInt}$ = Difference due to end-use demand per unit of activity, i.e. end-use "intensity"
$\Delta C_{EnergyEff}$ = Difference due to energy demand for each unit of end-use demand
$\Delta C_{FuelGHGInt}$ = Difference due to fuel GHG intensity per unit energy demand

We use the LMDI I approach to calculate the subcomponents of Equation (4) in Equations 5-11 because it is easy to use, robust, and has no residual term ($\Delta C_{Res} = 0$):

$$\Delta C_{Activity} = \sum \frac{C_{2050} - C_{2015}}{\ln\left(\frac{C_{2050}}{C_{2015}}\right)} \cdot ln\left(\frac{Activity_{2050}}{Activity_{2015}}\right) \tag{5}$$

$$\Delta C_{EndUseInt} = \sum \frac{C_{2050} - C_{2015}}{\ln\left(\frac{C_{2050}}{C_{2015}}\right)} \cdot ln\left(\frac{EndUseInt_{2050}}{EndUseInt_{2015}}\right) \tag{6}$$

$$\Delta C_{EnergyEff} = \sum \frac{C_{2050} - C_{2015}}{\ln\left(\frac{C_{2050}}{C_{2015}}\right)} \cdot ln\left(\frac{EnergyEff_{2050}}{EnergyEff_{2015}}\right) \tag{7}$$

$$\Delta C_{FuelGHGInt} = \sum \frac{C_{2050} - C_{2015}}{\ln\left(\frac{C_{2050}}{C_{2015}}\right)} \cdot ln\left(\frac{FuelGHGInt_{2050}}{FuelGHGInt_{2015}}\right) \tag{8}$$

The first term in each of the equations is the logarithmic mean of the difference in CO_2 emissions between 2015 and 2050. This value is multiplied by the natural log of the ratio of the factor in question, e.g., the ratio of 2015 activity to that of 2050, to calculate the influence of that factor on the difference in CO_2 per capita between the time periods.

Author statement

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Declaration of competing interest

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

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