Pathways to Mexico's climate change mitigation targets: a multi-model analysis

Veysey, J.; Octaviano, C.; Calvin, K.; Herreras Martinez, S.; Kitous, A.; McFarland, J.; van der Zwaan, B.

Published in:
Energy Economics

DOI:
10.1016/j.eneco.2015.04.011

Energy Economics 56 (2016) 587–599

Contents lists available at ScienceDirect

Energy Economics

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

Pathways to Mexico's climate change mitigation targets: A multi-model analysis☆

Jason Veysey [a,*], Claudia Octaviano [b,c], Katherine Calvin [d], Sara Herreras Martinez [e], Alban Kitous [f], James McFarland [g], Bob van der Zwaan [h,i,j]

[a] Stockholm Environment Institute, 11 Curtis Avenue, Somerville, MA 02144, United States
[b] Joint Program on the Science and Policy of Global Change, MA Institute of Technology, United States
[c] Mario Molina Center for Strategic Studies on Energy and the Environment, Mexico
[d] Joint Global Change Research Institute, Pacific Northwest National Laboratory/University of Maryland, 5825 University Research Ct, Suite 3500, College Park, MD 20740, United States
[e] Copernicus Institute of Sustainable Development, Utrecht University, Heidelberglaan 2, NL-3584 CS Utrecht, The Netherlands
[f] European Commission, DG Joint Research Centre (JRC), Institute for Prospective Technological Studies (IPTS), Unit J1 - Economics of Climate Change, Energy and Transport, Edificio Expo, C/ Inca Garcilaso, 3 E-41092 Sevilla, Spain
[g] U.S. Environmental Protection Agency, USEPA Headquarters, William Jefferson Clinton Building, 1200 Pennsylvania Avenue, N. W., Mail Code: 6207A, Washington, DC 20460 United States
[h] Energy Research Centre of the Netherlands (ECN), Policy Studies, Radarweg 60, 1043 NT, Amsterdam, The Netherlands
[i] Johns Hopkins University, School of Advanced International Studies, Bologna, Italy
[j] University of Amsterdam, Faculty of Science, Amsterdam, The Netherlands

ARTICLE INFO

Article history:
Received 29 August 2014
Received in revised form 15 April 2015
Accepted 18 April 2015
Available online 25 April 2015

JEL classification:
C61
Q41
Q42
Q43
Q47
Q48

Keywords:
Climate policy
Mexico
Modeling
Mitigation
Mitigation pathway

ABSTRACT

Mexico's climate policy sets ambitious national greenhouse gas (GHG) emission reduction targets—30% versus a business-as-usual baseline by 2020, 50% versus 2000 by 2050. However, these goals are at odds with recent energy and emission trends in the country. Both energy use and GHG emissions in Mexico have grown substantially over the last two decades. We investigate how Mexico might reverse current trends and reach its mitigation targets by exploring results from energy system and economic models involved in the CLIMACAP-LAMP project. To meet Mexico's emission reduction targets, all modeling groups agree that decarbonization of electricity is needed, along with changes in the transport sector, either to more efficient vehicles or a combination of more efficient vehicles and lower carbon fuels. These measures reduce GHG emissions as well as emissions of other air pollutants. The models find different energy supply pathways, with some solutions based on renewable energy and others relying on biomass or fossil fuels with carbon capture and storage. The economy-wide costs of deep mitigation could range from 2% to 4% of GDP in 2030, and from 7% to 15% of GDP in 2050. Our results suggest that Mexico has some flexibility in designing deep mitigation strategies, and that technological options could allow Mexico to achieve its emission reduction targets, albeit at a cost to the country.

1. Introduction

Mexico's national greenhouse gas (GHG) emission reduction goals align with the deep mitigation action required in climate stabilization scenarios and are among the most aggressive in the world, both for developed and developing regions. Importantly, they are significantly more ambitious than reduction targets in most other Latin American countries. While Mexico's policy has been recognized as a leading example in the region, emission trends in the country suggest that reaching the official targets will require a resourceful combination of actions and political agreements to redirect Mexico's economic growth to a low-carbon pathway. Energy demands and GHG emissions in Mexico have increased markedly in recent years, driven by expanding economic activity, a growing population, and rising standards of living. How can Mexico reverse current trends and substantially cut GHG emissions by mid-century? In this paper, we explore this question presenting an in-depth analysis of results for Mexico from selected policy scenarios of the CLIMACAP-LAMP cross-model comparison exercise.

The Climate Modeling and Capacity Building in Latin America project (CLIMACAP) and the Latin American Modeling Project (LAMP) are international research collaborations focused on improving the

☆ The views expressed are purely those of the author and may not in any circumstances be regarded as stating an official position of the European Commission.

* Corresponding author. Tel.: +1 617 627 3786.
E-mail addresses: jason.veysey@sei-us.org (J. Veysey), claus@mit.edu (C. Octaviano), katherine.calvin@pnnl.gov (K. Calvin), S.D.HerrerasMartinez@uu.nl (S.H. Martinez), alban.kitous@ec.europa.eu (A. Kitous), mcfarland.james@epa.gov (J. McFarland), vanderzwaan@ecn.nl (B. van der Zwaan).

http://dx.doi.org/10.1016/j.eneco.2015.04.011
0140-9883/

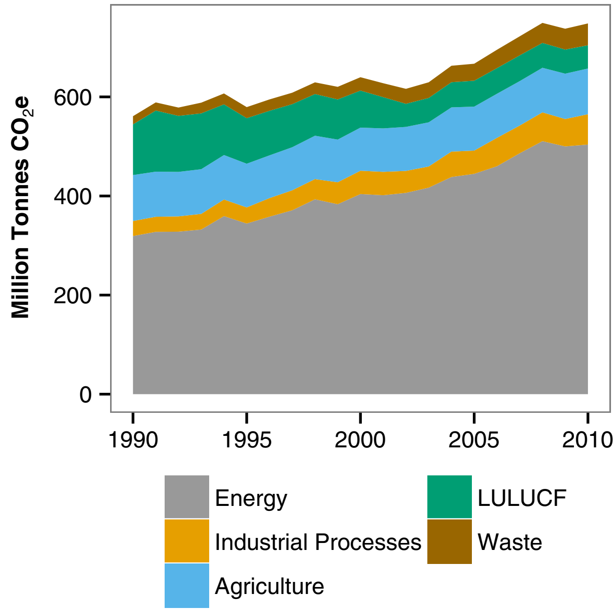

Fig. 1. Mexican GHG emissions by source. Source: SEMARNAT (2013).

modeling of energy systems, energy-economy interactions, and GHG emissions in Latin America. Funded by the U.S. Agency for International Development, the U.S. Environmental Protection Agency, and the European Commission, they involve modeling teams from many countries, including Mexico, Argentina, Brazil, Colombia, the US, and members of the European Union. Primarily through model intercomparisons (based on modeling a set of common scenarios) and joint investigations, participants seek to illuminate energy and climate policy questions of national, regional, and global significance. Both projects also emphasize dialogue with policy makers and contributing modeling results to the evidence base for policy making in Latin America.[1]

This paper is organized as follows. Section 2 describes GHG emission trends in Mexico and provides an overview of Mexican climate policy. Section 3 describes our cross-model comparison method, as well as the policy scenarios evaluated. Section 4 presents our results, describing the energy pathways that Mexico could follow to reduce emissions 50% with respect to its 2010 emissions by 2050. In this section, we provide an analysis of emission drivers, implications for energy supply and demand, and potential mitigation of non-energy GHGs and other air pollutants. Section 5 discusses policy costs, both from the macroeconomic perspective as well as for the energy system transition to low-carbon technologies. Section 6 concludes.

2. GHG emissions and climate policy in Mexico

2.1. GHG emissions

Annual GHG emissions in Mexico have risen sharply in the last two decades, growing 33% between 1990 and 2010 (Secretaría de Medio Ambiente y Recursos Naturales [SEMARNAT], 2013). The rate of emissions growth exceeds the world average and is more than four times that observed in other Organization for Economic Cooperation and Development (OECD) countries during the same period (European Commission, Joint Research Centre/PBL Netherlands Environmental Assessment Agency, 2011). Increased emissions from the production and use of energy account for the vast majority of the growth and today constitute two-thirds of the national total (Fig. 1).

Demographic and economic trends have played an important role in the emissions increase. Mexico's population grew nearly 40% from 1990 to 2010, to 112 million people, while real gross domestic product (GDP) per capita climbed 18% between 1993 and 2010 (Instituto Nacional de Estadística y Geografía [INEGI], 2014). As the population and economic activity have expanded, the demand for energy has grown alongside (Fig. 2).

The energy intensity of production (total energy demand / GDP) has remained essentially flat since the early 1990s, and energy demand per capita has grown (INEGI, 2013; SENER, 2014g). Between 1990 and 2010, total energy demand per capita increased 18%; excluding demand for non-energy purposes, such as chemical feedstocks, final energy demand per capita increased 6% (INEGI, 2014; SENER, 2014f,2014g). The transport sector has been a key contributor to rising demand, as Fig. 3 shows.

Although the GHG intensity of Mexico's energy supply (GHG emissions / energy used) is trending downward, decreasing close to 20% between 1990 and 2010, this effect has been outweighed by higher demand, producing the emissions profile in Fig. 1 (SEMARNAT, 2013; SENER, 2014g).

2.2. Climate policy

Recognizing the trends in national emissions and energy use and seeking to prevent dangerous climate change and promote low carbon development, the Mexican government has enacted a range of ambitious climate policies. At the center of these is the General Law on Climate Change (General Law), a statute adopted in 2012 and establishing the institutional and programmatic framework for national policy (SEMARNAT, 2012). At the institutional level, the General Law defines a National Climate Change System consisting of the following entities:

- **Inter-Ministerial Commission on Climate Change (ICCC)** – A commission of federal government ministries charged with developing and implementing national climate policy and helping determine Mexico's position in international climate negotiations
- **Climate Change Council** – A body advising ICCC and composed of leaders from the private sector, academia, and society at large
- **National Institute of Ecology and Climate Change (INECC)** – A federal agency with a mandate including climate change research and policy advice, GHG inventories and reporting under the United Nations Framework Convention on Climate Change (UNFCCC), and evaluation of climate change policies and programs
- State governments, representatives of national associations of municipal authorities, and representatives of the federal legislature

The System is a formal collaboration between these institutions, which are directed to develop and carry out policy via the three instruments summarized in Table 1 (SEMARNAT, 2012). As Table 1 suggests, regular updating of these instruments is envisioned, allowing the country's climate policy to adapt to changing conditions.

The General Law and the current National Strategy on Climate Change (published in 2013) set a number of national mitigation and adaptation goals. Significant quantitative goals for mitigation—the focus of this paper—are listed in Table 2.

Beyond the General Law and instruments arising from it, several other laws and programs also contribute to Mexico's climate policy. These measures support national efforts toward a clean energy transition and complement the quantitative climate policy objectives set by the General Law and its programs (Nachmany et al., 2014). For example, the 2008 Laws for Sustainable Energy Use and for the Use of Renewable Energies and Funding the Energy Transition encourage and regulate renewable energy and low-carbon electricity; while the 2002 General Law for Sustainable Forest Development promotes a variety of initiatives to reduce deforestation and forest degradation.

[1] For more on CLIMACAP, see http://climacap.org/.

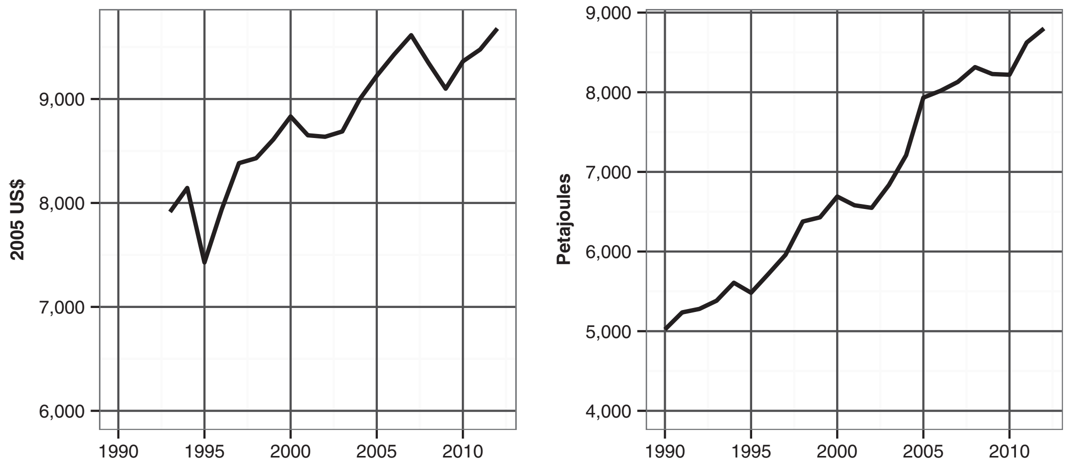

Fig. 2. Per capita GDP[a] (left) and total energy demand (right) in Mexico. Sources: INEGI (2013, 2014), Consejo Nacional de Población (2014), Secretaría de Energía [SENER] (2014g). [a]INEGI's publicly available GDP records begin in 1993.

The goals in Table 2 distinguish Mexico as a leader in mitigation policy. The overall emission reduction goals—30% by 2020, 50% by 2050—are among the most aggressive in the Americas and significantly more ambitious than reduction targets in other Latin American countries with high GHG emissions, such as Brazil, Argentina, and Venezuela (the last two have no formal reduction targets at all; Nachmany et al., 2014). Importantly for international climate negotiations, Mexico's reduction goals are in line with the deepest mitigation scenarios in the Intergovernmental Panel on Climate Change's (IPCC's) Fifth Assessment Report (AR5), including RCP2.6 and scenarios in the Working Group III 430–480 CO_2-equivalent (CO_2e) category (Clarke et al., 2014; Collins et al., 2013). These scenarios are premised on providing a good chance of limiting to 2 ° C the increase in global average temperature since pre-industrial times. They show worldwide GHG emissions falling about 50% between 2000 and 2050 (approximately 40 $GtCO_2e$ / year to approximately 20 $GtCO_2e$ / year), which corresponds neatly to Mexico's 2050 objective (Clarke et al., 2014, p. 25). This result is suggestive, although it admittedly does not account for equity and effort-sharing principles that may imply that Mexico's reductions should be more or less than a typical country's. However, Clarke et al. (2014) also survey the effort-sharing literature and report that under a range of effort-sharing regimes, Latin American countries must cut emissions in 2050 between about 35% and 70% relative to 2010 (20th percentile to 80th percentile for the studies evaluated; p. 59). Mexico's 2050 goal equates to a 57% decrease versus 2010, well within this interval.

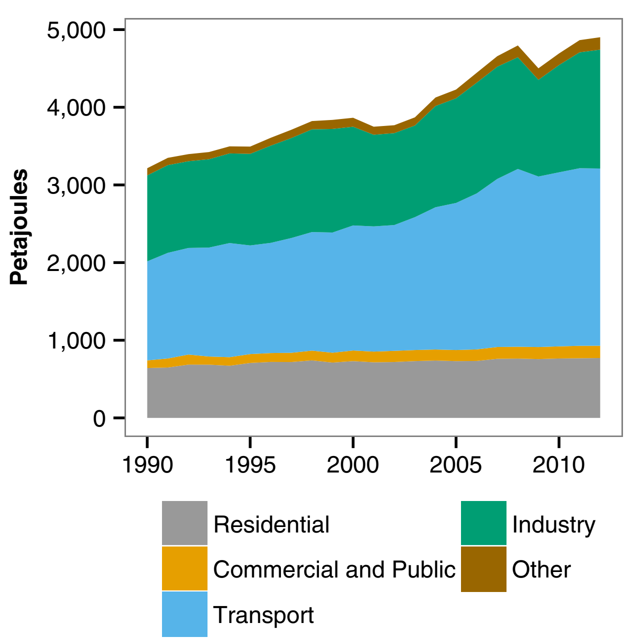

Fig. 3. Final energy demand in Mexico by sector. Source: SENER (2014f).

Perhaps with comparisons like these in mind, the Mexican government has stated that it hopes to lead the international community by example on climate. As the current National Strategy on Climate Change puts it, "the country is moving forward in the fulfillment of its international commitments. [The Strategy] will also be, as it is executed, the best argument to demand collective action from the international community against climate change" (Federal Government of Mexico, 2013, p. 9). The strategic value of an ambitious climate program is especially relevant as negotiations over the next UNFCCC agreement enter their final stages.

3. Cross-model methodology and policy scenarios

The models in our study employ state-of-the-art techniques to assess mitigation policy and include models with detailed representations of the energy sector, economy-wide models with the capability of assessing interactions in all sectors of the economy and international trade, and hybrid models that incorporate details of both energy systems analysis and the interaction of energy and climate policy with the rest of the economy. In all, six models provided results for this paper. Each represents Mexico as a separate country alongside other

Table 1
Key policy instruments defined in general Law on climate change.

National Strategy on Climate Change	• Plan governing policy in the medium to long term • Prepared by SEMARNAT with INECC and the Climate Change Council, approved by ICCC • Covers climate scenarios, resource and land-use trends, GHG emissions and mitigation potential (including emission projections), vulnerability assessment, mitigation and adaptation goals, and policy implementation progress • Mitigation content reviewed and updated at least every 10 years; adaptation content reviewed and updated at least every 6 years
Special Climate Change Program	• Short-term implementation plan for federal policies (six-year horizon) • Developed by SEMARNAT with ICCC, approved by ICCC • Must agree with the National Strategy
State and municipal climate change programs	• Implementation plans for state and municipal policies • Must agree with the National Strategy and the Special Climate Change Program

Source: SEMARNAT (2012).

Table 2
Quantitative mitigation goals in general law on climate change and national strategy on climate change.

2018	• Cities with more than 50,000 inhabitants emit no methane from solid waste management
2020	• 30% reduction in national GHG emissions versus a business-as-usual baseline (equates to a 5% increase compared to emissions in 2000 and a 10% decrease compared to emissions in 2010)[2]
	• No further carbon loss from "original" ecosystems (i.e., ecosystems not degraded by human activity)
2024	• 35% of national electricity from clean sources
2030	• 40% of national electricity from clean sources
	• No net deforestation
	• Negative emissions (net sink) from forestry
2050	• 50% reduction in national GHG emissions versus 2000
	• 50% of national electricity from clean sources

Sources: SEMARNAT (2012), Federal Government of Mexico (2013).

regions. For full details on each model, including mathematical formulations, simulation or optimization algorithms, and datasets used, we refer to existing publications by the modeling teams: EPPA (Paltsev et al., 2005), GCAM (Wise and Calvin, 2011), IMAGE (Bouwman et al., 2006), Phoenix (Sue Wing et al., 2011), POLES (Kitous et al., 2010), and TIAM-ECN (Kober et al., 2014; Rösler et al., 2014; van der Zwaan et al., 2013). A brief summary of some key features of the models is shown in Table 3.

As outlined in the preface to this issue, modeling teams in the CLIMACAP-LAMP project have evaluated a variety of scenarios of future energy demand, climate policy, and GHG emissions in Latin America (van der Zwaan, 2016-this issue). Here we focus on three in particular:

1) Core Baseline: A business-as-usual scenario including climate and energy policies enacted prior to 2010.
2) 50% Abatement (GHG): A scenario in which GHG emissions, excluding CO_2 from land use change, are reduced by 12.5% in 2020, linearly increasing to 50% in 2050, with respect to 2010.
3) 50% Abatement (FF&I): A scenario in which fossil fuel and industrial CO_2 emissions are reduced by 12.5% in 2020, linearly increasing to 50% in 2050, with respect to 2010.

We use the Core Baseline scenario as a reference when analyzing mitigation pathways and the 50% Abatement scenarios, which align generally with Mexico's long-term GHG emission reduction target, to explore the technical and economic implications of deep mitigation. Results from 50% Abatement (FF&I) are reported for the one model that does not represent emissions of non-CO_2 GHGs (Phoenix), while results from 50% Abatement (GHG) are presented for the five other models.[3]

All six models report emissions from energy use and apply scenario targets to emissions from energy use. Reporting of non-energy emissions is fragmentary, but scenario targets are applied to non-energy emissions when models include them. Other important assumptions in the scenario design include: a) for global models that can represent international and regional policies, the same carbon constraints are imposed in the rest of the world; b) carbon trade between Latin American countries and between non-Latin American countries is allowed, but Latin American countries do not trade with non-Latin American countries[4]; and c) land-use CO_2 emissions are not subject to carbon constraints.

Table 3
Key model features.

Model/institution	Model type	Regions	Main low carbon technologies
EPPA *Massachusetts Institute of Technology, United States*	Global general equilibrium model (16 economic sectors) with a hybrid approach including engineering information to model the energy sector and land-use changes	16 regions including Mexico and Brazil	Gas with carbon capture and storage (CCS) Coal with CCS Wind Solar Biomass Hydro Nuclear Biofuels Hybrid vehicles
GCAM *Pacific Northwest National Laboratory, United States*	Global energy system and land use model with a reduced-form representation of the carbon cycle and climate	32 regions including Mexico, Argentina, Brazil, and Colombia	Gas with CCS Coal with CCS Wind Solar Biomass Biomass with CCS Hydro Nuclear Biofuels
IMAGE *Netherlands Environmental Assessment Agency, The Netherlands*	Global energy model, with a sub-model for land use and land cover and a sub-model that distributes emissions based on marginal abatement costs	26 regions including Mexico and Brazil	Gas with CCS Coal with CCS Wind Solar Biomass Hydro Nuclear Biofuels
Phoenix *Penn State University, United States*	Global general equilibrium model (26 economic sectors)	26 regions including Mexico, Brazil, Colombia, and Venezuela	Advanced gas Gas with CCS Coal with CCS Wind Solar Biomass Hydro Nuclear Biofuels Hybrid vehicles
POLES *ENERDATA, United Kingdom*	Energy market equilibrium model with econometric functions for consumption patterns	50 regions including Mexico and Brazil	Gas with CCS Coal with CCS Wind Solar Biomass Hydro Nuclear Biofuels Hybrid vehicles
TIAM-ECN *Energy Research Centre of the Netherlands, The Netherlands*	Global bottom-up linear optimization energy system model	20 regions including Mexico, Argentina, Brazil, Chile, Colombia	Gas with CCS Coal with CCS Wind (onshore and offshore) Solar photovoltaic (PV) Concentrated solar power (CSP) Biomass Hydro Nuclear Biofuels Advanced vehicle technologies, including hybrid, battery electric, and hydrogen

Results from these models and scenarios shed light on the pathways Mexico could follow to attain its long-run mitigation objectives. We characterize potential pathways in terms of their assumptions about social and economic conditions; changes in energy intensity, fuel mixes, and technology deployment; non-energy GHG emissions; economic impacts; and co-benefits, such as reduced emissions of short-lived climate pollutants. While the paths that emerge from the models are not the

[2] As described in Federal Government of Mexico (2013), the business-as-usual baseline is "a trend projection of GHG emissions in [the] absence of mitigation actions" (p. 46). It assumes annual GDP growth of 3.6% and accounts for historical emissions, expected increases in population, and energy sector policies and plans.

[3] For notational simplicity, we refer to these two scenarios jointly as the "50% Abatement scenario" when discussing results.

[4] Trading of CO_2 and non-CO_2 emissions is permitted using IPCC global warming potentials to estimate CO_2e. The availability of trade lowers the global costs of attaining the 50% Abatement targets and means that the level of abatement physically realized in each country or region may be higher or lower than the targets.

Table 4
Real GDP – annual average growth rates.

Historical (1993–2012)	IMF World Economic Outlook Projection (2013–2019)	Model projections in 50% abatement scenario (2010–2050)					
		EPPA	GCAM	IMAGE	Phoenix	POLES	TIAM-ECN
2.6%	3.5%	3.1%	2.0%	3.9%	3.2%	3.3%	3.1%

Sources: INEGI (2013), IMF (2014), CLIMACAP-LAMP (2015).

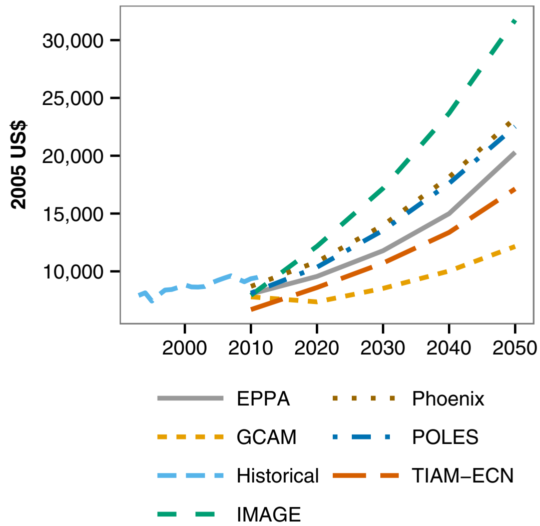

Fig. 4. Per capita GDP projections in 50% abatement scenario. Sources: CLIMACAP-LAMP (2015); historical – INEGI (2013, 2014), Consejo Nacional de Población (2014).

only ways Mexico could achieve its goals, they are a useful reference for evaluating the scale of the required transformation and trade-offs faced by Mexican policy makers and society as a whole.

4. Mitigation pathways to 2050

4.1. Economic and social context

As noted in Section 2, increasing population and rising standards of living in Mexico have been important factors driving growth in GHG emissions. The extent to which these socioeconomic trends continue in the future will clearly affect the outlook for emission reductions. Critically, in the 50% Abatement scenario, all six CLIMACAP-LAMP models envision population and income growing as they have historically. Population generally continues on the trajectory it has taken since 1990, reaching about 150 million by 2050 (about 125 million in IMAGE; CLIMACAP-LAMP, 2015). Meanwhile, real GDP increases at a rate comparable to those reported in Mexico's official statistics and by international institutions such as the International Monetary Fund (IMF; Table 4).

Projections of total GDP in 2050 in the 50% Abatement scenario range between $2 trillion (GCAM) and $4.1 trillion (IMAGE) 2005 USD (compare to the official 2010 GDP from INEGI, $1.1 trillion 2005 USD; CLIMACAP-LAMP, 2015; INEGI, 2013). Taken together, the estimates of production and population produce the GDP per capita projections shown in Fig. 4.[5]

Every model anticipates greater personal income accompanying an expanding population; in most cases, real personal income more than doubles between 2010 and 2050.[6]

As consumer income increases, however, real energy prices do as well. Table 5 characterizes real prices for electricity and major fuels in the 50% Abatement scenario. The prices are indexed to their 2010 values, and darker shading indicates a greater increase relative to 2010.

While the models do not align exactly, there is general agreement on significant, long-term real price increases for biomass and modest-to-sizeable increases for natural gas and oil. The majority of models also foresee higher real prices for electricity and coal by 2050, although the magnitude of the price growth varies. Multiple model-specific factors underlie these changes, including assumed mitigation policies, but their net effect offsets to some degree the impact of rising consumer income.

4.2. Energy supply

As shown in Fig. 1, energy emissions constitute the largest share of GHG emissions in Mexico. In order to reach a 50% emission reduction, Mexico will have to transform its energy supply to low-carbon energy technologies. In this section, we focus on the transition of the power system to clean technologies and present impacts to the oil sector.

In 2013, Mexico's total electricity generation was 257.9 TWh (SENER, 2014h); Fig. 5 shows the mix by fuel used. Fossil fuels accounted for 82% of total generation, with the rest coming from hydro, nuclear, and other renewables. As shown in Fig. 5, the most important share of generation was for natural-gas combined cycle units, with 49% of generation, followed by 18% for fuel oil, 12% for coal (including dual units that generate with fuel oil and coal), 11% for hydropower, and 5% for nuclear. Other renewables in the country, mainly geothermal and wind, produced 3% of the total.

Mexico is transitioning away from fuel oil generation and rapidly investing in natural gas, both in terms of generation facilities as well as the associated infrastructure to supply gas (e.g., pipelines and liquefied natural gas terminals). Current programs from the energy sector suggest that the business-as-usual trend for power generation will rapidly transform Mexico to a natural gas based system, particularly given current prices of natural gas in North America. In recognition of potential issues for energy security and climate change, the government is implementing environmental and energy policies to promote energy diversification and the use of clean energy sources,[7] as described in Section 2. Results include programs to promote wind generation in sites with high wind potential, such as Oaxaca state and Baja California, and the 39 MW Aura Solar I plant in Baja California Sur. Our modeling results project a diversity of possible futures for Mexico's power system. First, varying assumptions about economic growth and potential efficiency measures result in a wide range of projected electricity supply requirements. As shown in Fig. 6, total generation is projected in the baseline scenario between 2.0 EJ (EPPA) and 4.3 EJ (POLES). In the 50% Abatement scenario, the range of electricity supply also varies shifting downwards to 1.1 EJ (EPPA) and 4.1 EJ (POLES). This comes as a result

[5] Fig. 4 and subsequent figures in this paper show that 2010 values in the six models sometimes differ from each other and from official government numbers. This variation is due to differences in the input data and assumptions used to construct and calibrate the models' baselines (for more on the models' baselines, see van Ruijven et al., 2016-in this issue. For GHG emissions specifically, the models report 2010 values that range between about 80% [TIAM-ECN] and 101% [POLES] of the government estimate. As a result they do attain different absolute emission reductions in the 50% Abatement scenario although they are targeting the same percent reduction.

[6] The notably high projection in IMAGE is due in part to high total GDP but also in part to lower projected population.

[7] Mexico's Special Climate Change Program and Special Program on Renewable Energy specify targets both for emissions intensity of generation and for total generation from renewables and from clean energy sources.

Table 5
Real energy prices in 50% abatement scenario (2010 value in model = 100)[a].

	EPPA		GCAM		IMAGE		Phoenix		POLES		TIAM-ECN	
	2020	2050	2020	2050	2020	2050	2020	2050	2020	2050	2020	2050
Biomass[b]	NR[c]	NR	105	218	117	235	NR	NR	114	183	532	3218
Coal[d]	76	47	101	99	113	125	97	150	108	109	120	575
Gas[d]	106	101	101	113	120	188	103	103	124	193	178	281
Oil[d]	125	158	103	114	123	149	102	104	127	190	111	120
Electricity[e]	76	152	108	94	158	97	127	177	199	181	967	803

Source: CLIMACAP-LAMP (2015).
[a]Light shading: 110 ≤ value < 150; medium shading: 150 ≤ value < 200; dark shading: 200 ≤ value.
[b]Producer price (except for IMAGE, which reported price for large consumers only)
[c]NR = not reported
[d]Spot price in global or regional market
[e]Price for large consumers

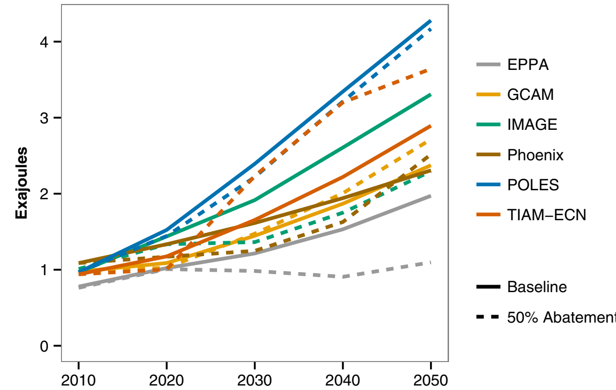

Fig. 6. Total electricity generation in core baseline and 50% abatement scenarios. Source: CLIMACAP-LAMP (2015).

of induced energy efficiency (as we will discuss in the next section), but also as a result of decreases in economic activity in the country and globally due to pricing carbon. While the envelope of total electricity supply provides a range of potential expected generation in the baseline and mitigation scenarios, it is worth highlighting some differences in the trends of the models. POLES, IMAGE, and EPPA project a decrease in total electricity supply in the 50% Abatement scenario, while GCAM, Phoenix, and TIAM-ECN project an increase. In these last three models, electrification becomes an important mitigation option driving electricity demand upwards (as explained in the next section, electrification also occurs in the other models; however, it is outweighed by other dynamics such as energy efficiency).

The generation mix also varies between the models in the baseline scenario (Fig. 7). GCAM and EPPA find that natural gas will dominate the mix in 2050 in the baseline case, with EPPA having the highest share of gas at 74%. All other models find a relevant participation of this fuel. The model that expects the least amount of gas in the electricity mix is TIAM-ECN, projecting only 27%. All models estimate coal to be used in the baseline case as well, from 10% (EPPA) to 50% (TIAM-ECN). All models, except for Phoenix, find a minor share for oil-fired generation; the range is from less than 1% (IMAGE) to 28% (Phoenix). In terms of renewables, the models vary widely. Both POLES and IMAGE find significant participation by renewables, although the selection of technologies differs. IMAGE chooses onshore wind and biomass, and

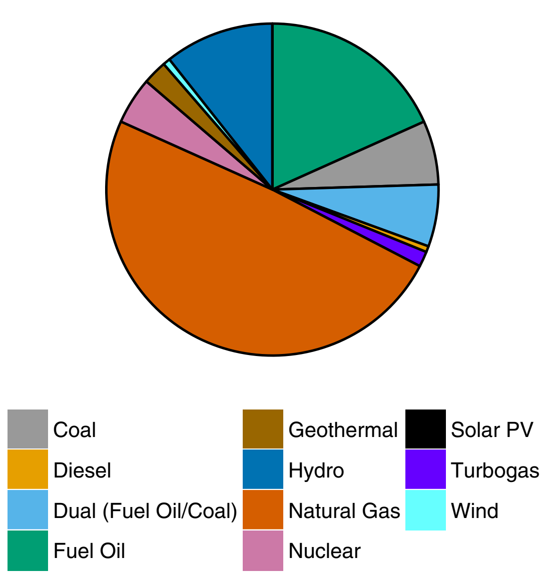

Fig. 5. Total electricity generation in Mexico in 2013. Source: SENER (2014h).

POLES opts primarily for solar technologies and wind. GCAM and TIAM-ECN also find a relevant participation of renewables in the baseline, of 24% and 14%, respectively. GCAM deploys biomass, geothermal, wind, solar, and hydro, while TIAM-ECN mainly chooses wind and hydro. In all, the models find a range from 8% participation of renewables (EPPA) to 43% participation (IMAGE) in the baseline. Results from some of the models therefore suggest that renewables will be competitive without climate policy, to a certain extent, although this is not the case in all models.

The 50% Abatement scenario drastically changes the electricity technology choices in all models. By 2050, POLES and TIAM-ECN find mixes dominated by renewable energy, primarily by solar technologies of which photovoltaic (PV) has the biggest share, and some participation of wind and biomass. IMAGE also finds renewable energy dominates; however, this model does not deploy much solar technology and instead relies on biomass and wind. GCAM deploys natural gas with CCS, biomass with CCS, nuclear, and some wind and solar. Phoenix substantially reduces oil-fuel generation and opts for coal CCS and wind. EPPA projects a significant decrease in total electricity supply, due to efficiency and demand adjustments, and deploys primarily natural gas with CCS, followed by hydro, coal with CCS, and a phase-out of fuel oil generation.

The models arrive at these endpoints by considering a number of factors, including assumed costs, electricity requirements, mitigation objectives, and production constraints such as natural resource availability, technology availability, and limits on the rate of grid integration of certain technologies. For example, biomass supply in IMAGE is limited by land available for raising energy crops (defined as abandoned agricultural land and part of the natural grasslands in divergent land-use scenarios), the productivity of available land, and energy losses during the conversion of crops to fuels (Bouwman et al., 2006). Kober et al. (2016-in this issue) summarize the natural resource and other electricity production constraints operative in the models. With respect to costs, it is important to note that relative costs, not absolute costs, drive technology choice in any given model. Thus, for instance, the models that opt for CCS in preference to renewables estimate that it is a more cost-effective way to achieve deep emission reductions (accounting for issues like the intermittency of renewables, transmission and distribution costs, and so forth), not that CCS is inexpensive in an absolute sense. The possibility of net negative GHG emissions with biomass CCS (described further below) also has significant option value because it provides flexibility in sectors where abatement is difficult (e.g., transport; Kriegler et al., 2014).

A key point of agreement, however, is that all models find significant decarbonization of electricity is necessary to cut Mexico's GHG emissions by 50%. Table 6 shows the percentage of power generated from clean sources in the 50% Abatement scenario, defining "clean" as in

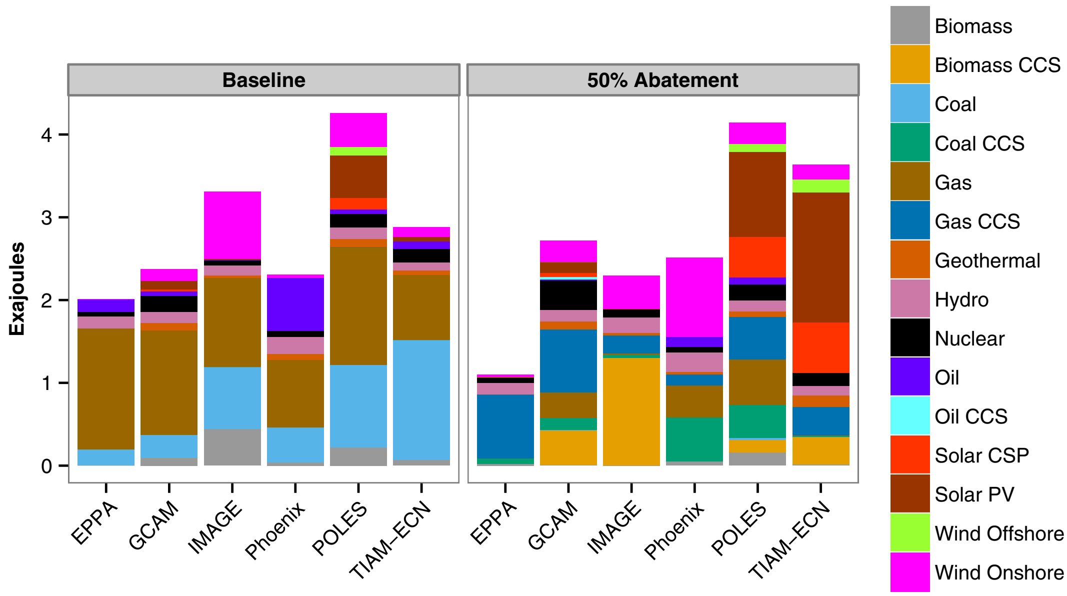

Fig. 7. Electricity generation in 2050 by technology and scenario. Source: CLIMACAP-LAMP (2015).

Table 6
Percentage of power generated from clean sources in 50% abatement scenario vs. national targets.

	2020	2024	2030	2040	2050
National Targets		35%	40%		50%
EPPA	20%		22%	98%	100%
GCAM	31%		57%	76%	88%
IMAGE	22%		31%	63%	99%
Phoenix	27%		32%	57%	80%
POLES	30%		60%	82%	84%
TIAM-ECN	37%		91%	100%	100%

Sources: CLIMACAP-LAMP (2015); national targets – SEMARNAT (2012), Federal Government of Mexico (2013).

Table 7
Emission intensity of electricity supply in 2050 under 50% abatement scenario.

	EPPA	GCAM	IMAGE	Phoenix	POLES	TIAM-ECN
Generation (TWh)	305	754	637	699	1158	1012
Emissions ($Mt\ CO_2$)	10.0	−40.7	−291.7	53.7	55.5	−76.7
Emission intensity ($Mt\ CO_2$ / TWh)	0.03	−0.05	−0.46	0.08	0.05	−0.08

Source: CLIMACAP-LAMP (2015).

Mexico's recently enacted Electricity Industry Law[8] and comparing the models' results to targets in the General Law on Climate Change and National Strategy on Climate Change.

Although the 50% Abatement scenario does not include the national targets as explicit constraints, the modeled results agree with the nearest-term target (for 2024) and are distributed around the 2030 target. By 2050, however, they differ systematically from the national goal, all models envisioning a share of power from clean sources substantially higher than 50%. Another way of thinking about the projected changes in the power sector is in terms of emissions. To reduce economy-wide emissions 50% by 2050, all models find that CO_2 emissions from electricity generation must decrease by more than 50% (relative to both the baseline scenario and 2010 emissions). These findings suggest that attaining 50% clean generation by 2050 will not suffice to reach the overall abatement target for the economy.

Another indicator that the Mexican government has mooted is the emission intensity of the power mix. Emission intensity of electricity generation in the country in 2013 was 0.456 t CO_2e / MWh, as reported in the Special Climate Change Program (SEMARNAT, 2013). Table 7 shows how models compare in this indicator for the 50% Abatement scenario. Phoenix reports the highest emission intensity (0.08 Mt CO_2 / TWh), followed by POLES (0.05), and EPPA (0.03). Interestingly, three models in our comparison exercise find that the power sector will have to have negative emissions to reach the reduction target, with IMAGE having the largest negative emissions followed by TIAM-ECN and GCAM.

Regarding the oil sector, the 50% Abatement scenario implies a reduced role for oil in all models (Fig. 8). Relative to the baseline scenario, IMAGE expects the amount of oil in the total primary energy supply to be 82% lower in 2050; Phoenix projects a 67% decrease, TIAM-ECN 66%, EPPA 48%, GCAM 32%, and POLES 21%. The shift away from oil is due to electrification; more use of biomass; alternative transport technologies; and energy efficiency in transportation, buildings, and industry, as we explain in the next section.

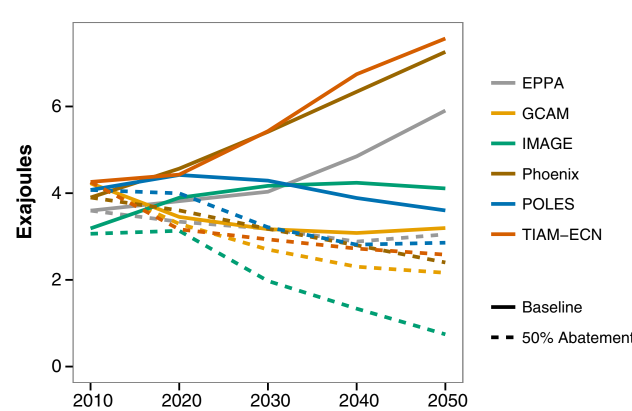

Fig. 8. Oil in primary energy supply in core baseline and 50% abatement scenarios. Source: CLIMACAP-LAMP (2015).

[8] Per the Law, clean energy sources include non-biomass renewables, biomass, nuclear, and CCS technologies (Secretaría de Gobernación, 2014).

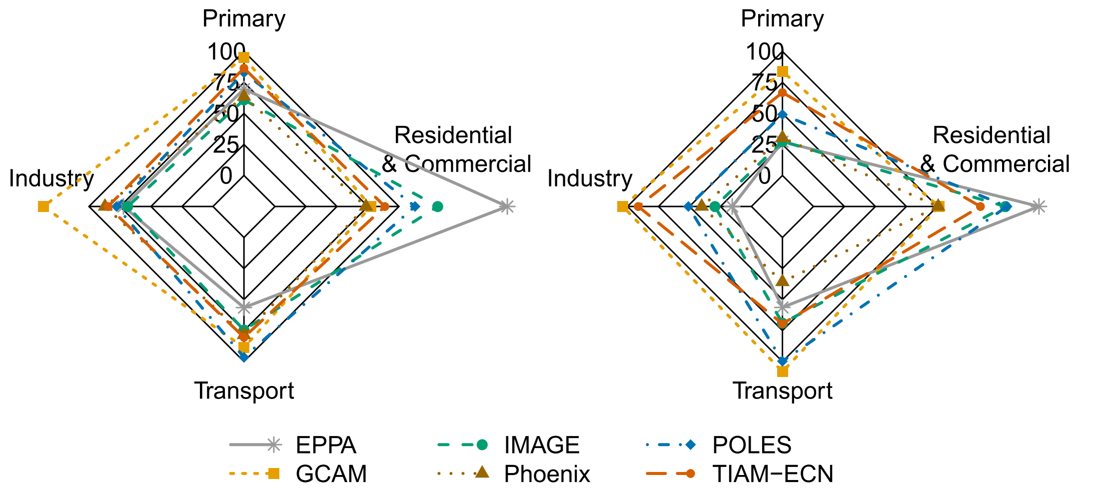

Fig. 9. Energy intensity metrics in 50% abatement scenario in 2020 (left) and 2050 (right) (2010 value = 100)[a]. Sources: CLIMACAP-LAMP (2015); 2010 metrics – SENER (2014f, 2014g), INEGI (2013, 2014). [a]Industrial demand includes feedstocks and demand for agriculture and fishing.

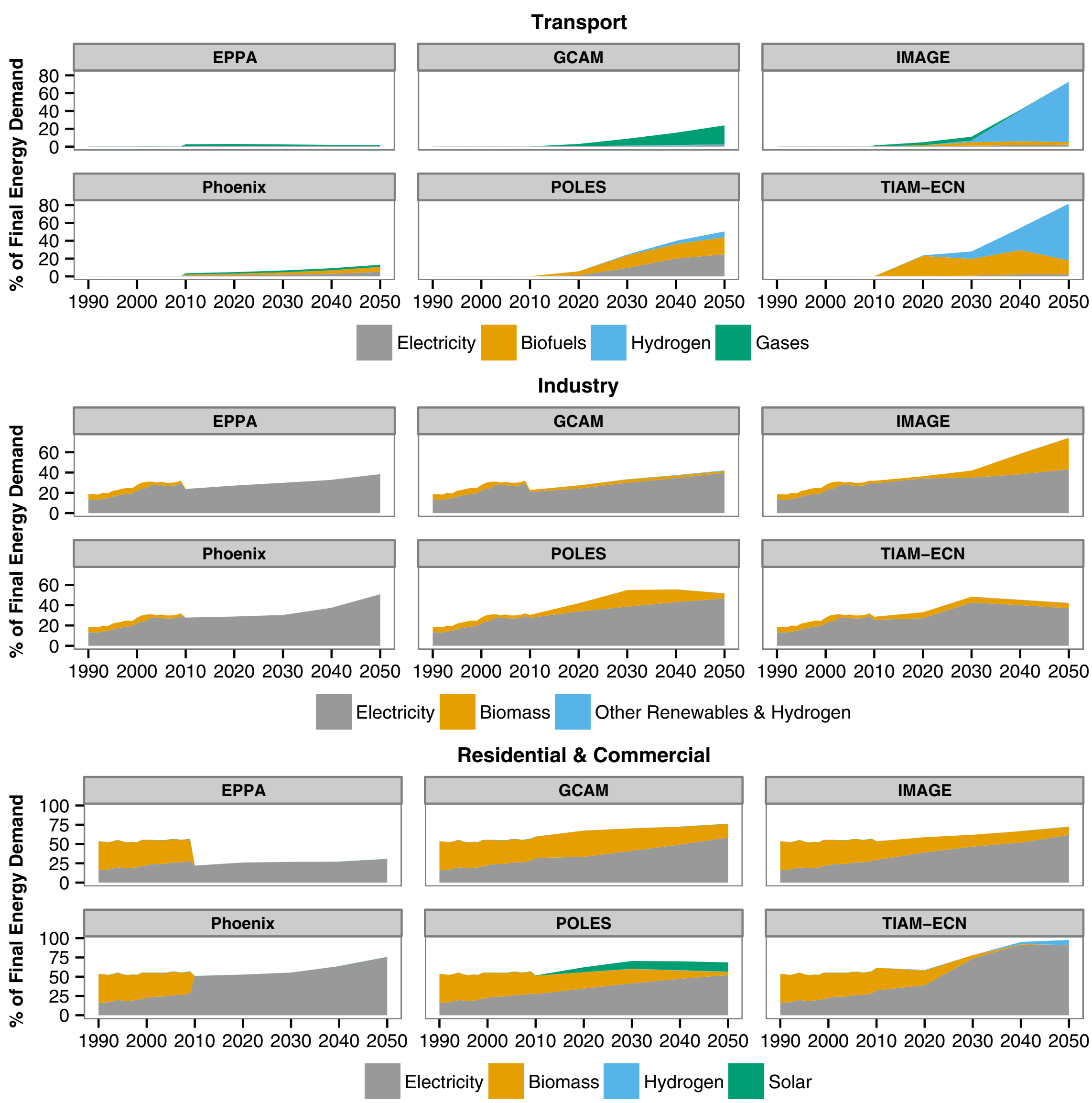

Fig. 10. Demand for lower carbon and alternative fuels in 50% abatement scenario[a]. Sources: CLIMACAP-LAMP (2015), SENER (2014a, 2014b, 2014c, 2014d, 2014e). [a]Industrial demand includes feedstocks and demand for agriculture and fishing.

4.3. Energy demand

All of the CLIMACAP-LAMP models indicate that demand-side measures are an integral part of a mitigation pathway for Mexico. Results from the 50% Abatement scenario show substantial changes in demand-side energy intensity and fuel mixes, implying important technological and behavioral shifts. However, the models differ in the emphasis they place on efficiency versus fuel and equipment switching as well as in the impact projected in Mexico's main energy-consuming sectors—transport, industry, and the residential and commercial sectors.

Fig. 9 summarizes four key energy intensity metrics from the 50% Abatement scenario: national primary energy demand / GDP (Primary), industrial final energy demand / GDP (Industry), transport final energy demand / population (Transport), and residential and commercial final energy demand / population (Residential & Commercial). Each metric is indexed to its 2010 value as calculated from official Mexican government sources. The panel on the left shows projected values in 2020, while that on the right shows values in 2050.

Several points emerge from this graph. Most models anticipate some improvement in energy intensity by 2020 and a substantially greater improvement by 2050. There are exceptions, though: GCAM counts on little or no decrease in intensity even by 2050; and POLES and TIAM-ECN project more modest improvements than Phoenix, IMAGE, and EPPA in the long run. On a sectoral level, results vary widely for industry and transport—ranging from no change in energy per GDP or person to decreases of 50–75% or more—while none of the models foresee a significant reduction in residential and commercial energy intensity. In many models, in fact, residential and commercial intensity increases by 2050, an outcome that may be due to rising per capita income.

Fig. 10 shows projected shifts to lower carbon and alternative fuels in the transport, industrial, and residential and commercial sectors. Data for 1990–2009 are from SENER; data for 2010 and later are from the 50% Abatement scenario.

The general trend in all models is toward increased penetration of lower carbon fuels and technologies, in some cases with an acceleration of adoption after 2020 or 2030. The models differ most markedly in the transport sector: EPPA, GCAM, and Phoenix project relatively little fuel and technology switching, while the other models envision substantial changes by 2050. IMAGE anticipates a wholesale shift to hydrogen, TIAM-ECN near-term penetration of biofuels and later uptake of hydrogen, and POLES a more balanced adoption of electricity, biofuels, and some hydrogen. In the industrial and residential and commercial sectors, all models foresee continued electrification, with the 2050 share of electricity in final energy demand in many instances approaching or exceeding 50%. There is some disagreement about the role of biomass, although in the residential and commercial sector biomass use declines over time in all models (reflecting decreased use of traditional biomass). With one exception (residential and commercial solar in POLES), no models expect significant contributions from hydrogen or non-biomass renewables.

4.4. Non-energy GHG emissions

As mentioned earlier, the CLIMACAP-LAMP models differ in their coverage of non-energy GHG emissions. Notwithstanding, a reasonable number (all except Phoenix) do report results for emissions from agriculture and land use, which constitute the majority of Mexico's non-energy GHG emissions (Fig. 1). In the 50% Abatement scenario, the trajectory followed in this category varies widely across models.[9] Table 8 summarizes the percent change in total GHG emissions from agriculture and land use between 2010 and 2050, taking the 2010 value from Mexican government sources.

[9] We note again that the 50% Abatement scenario does not apply emission reduction constraints to CO_2 emissions from land use. However, the constraints do apply to emissions of other GHGs from land use as well as to all agricultural emissions.

Table 8
Percent change in GHG emissions from agriculture and land Use between 2010 and 2050, 50% abatement scenario.

EPPA	GCAM	IMAGE	POLES	TIAM-ECN
−12.5%	−10.5%	−121.4%	−84.7%	−35.0%

Sources: CLIMACAP-LAMP (2015), SEMARNAT (2013)

These results suggest there are at least some paths to deep mitigation for Mexico that do not depend on substantial reductions in non-energy emissions.

4.5. Emissions of other Air pollutants

Cutting emissions of GHGs with long-term warming potential frequently leads to reduced emissions of other air pollutants as well (Clarke et al., 2014). In Mexico, such effects are an explicit focus of climate policy: one of the five "strategic axes" of the country's mitigation policy is to "[r]educe emissions of Short-Lived Climate Pollutants (SLCPs), and promote co-benefits in health and well-being" (Federal

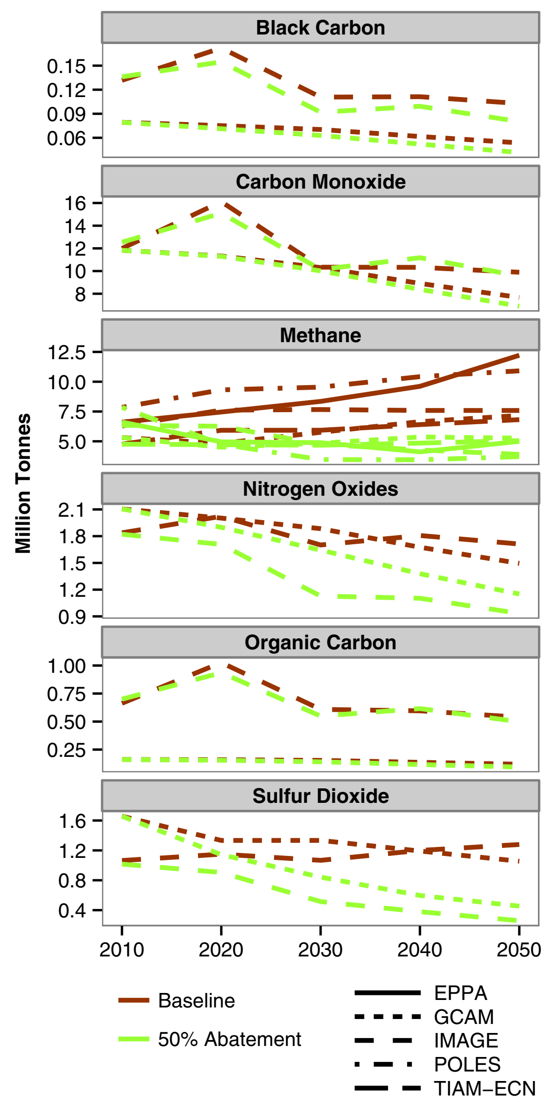

Fig. 11. Emissions of other air pollutants in core baseline and 50% abatement scenarios. Source: CLIMACAP-LAMP (2015).

Government of Mexico, 2013, p. 20). SLCPs include black carbon, methane, hydrofluorocarbons, and tropospheric ozone, the latter commonly formed in the atmosphere by interaction of methane, carbon monoxide, nitrogen oxides, and other gases (Climate and Clean Air Coalition to Reduce Short Lived Climate Pollutants [CCAC], 2014). In addition to a short-run impact on climate, these pollutants have a variety of harmful health and environmental consequences (CCAC, 2014).

The CLIMACAP-LAMP models offer some estimates of emissions of SLCPs, ozone precursors, sulfur dioxide, and organic carbon in the baseline and mitigation scenarios (Fig. 11). The available results indicate that emissions of these pollutants are indeed lower in the mitigation scenario than under business-as-usual conditions, notwithstanding decreasing emissions for several of the pollutants in the baseline. The general agreement among models suggests air pollution co-benefits along a range of mitigation pathways. The highest average emission reductions across models in 2050 are reported for sulfur dioxide (68% reduction), methane (45% reduction), and nitrogen oxides (34% reduction), indicating greater abatement potential for these gases under mitigation policy.

4.6. Summary of mitigation pathways

Surveying the results in the previous subsections makes clear that each of the CLIMACAP-LAMP models takes a quite different path to significant mitigation by 2050. These paths have some common elements but vary considerably in their technical and sectoral emphases. The emergent commonalities suggest that a route to Mexico's 2050 goal may have some core features. In a future where Mexico's population, GDP, and GDP per capita are all significantly higher, most or all models find in the 50% Abatement scenario:

- Significantly higher electricity demand over time coupled with decarbonization of the electricity supply (GHG emissions per generated MWh falling 80% or more between now and 2050)
- Widespread deployment of new low-carbon technologies in the power sector, including CCS technologies
- A decrease in the amount of oil in the primary energy supply
- Increased overall penetration of lower carbon fuels and technologies in industry, transport, and the residential and commercial sector (but with large differences over the specific fuels and technologies deployed)
- In the industrial and residential and commercial sectors, continued electrification of energy end uses – with electricity's share of final energy growing at least as fast as it has over the last two decades
- Air pollution co-benefits relative to the baseline scenario, notably reductions in emissions of sulfur dioxide, methane, and nitrogen oxides
- No substantial contributions from non-biomass renewables or hydrogen in final energy for industry and buildings
- A decline in the use of traditional biomass in the residential and commercial sector
- Important long-term real price increases for electricity and biomass together with somewhat smaller long-term real price increases for natural gas and oil

Beyond this basic agreement, however, each model's solution has distinctive features as summarized in Table 9.

Table 9
Distinctive features of mitigation pathways.

Model	Features
EPPA	• Electricity generation in 2050 dominated by gas CCS • Significant energy intensity improvements overall and in industry and transport • Lowest electricity supply requirements of all models owing to demand-side responses • Very high capital investment in transportation to deploy efficient vehicles • Relatively lower real fuel price increases than most other models, except for oil
GCAM	• Lowest per capita income projection of all models • Modest fuel price increases except for biomass in long term • Electricity generation in 2050 led by gas CCS, biomass CCS, and more nuclear than any other model (electricity generation becomes a net GHG sink) • Little or no energy intensity improvement per any of the metrics considered • Very modest fuel switching in transport (to gas)
IMAGE	• Highest per capita income projection of all models • Fairly large fuel price increases across the board (except for electricity) • Electricity generation in 2050 dominated by biomass CCS with some wind (electricity generation becomes a net GHG sink) • Biomass also plays an important role in industrial final energy by 2050 • Substantial energy intensity improvements overall and in industry • Most transport powered by hydrogen by 2050 (almost 70%) • Lowest primary demand for oil of all models • Very large decrease in non-energy emissions from agriculture and land use
POLES	• Large fuel price increases in near and long term, except for coal • Greatest projected electricity requirements – about four times higher in 2050 than at present • Electricity generation in 2050 emphasizes non-biomass renewables (primarily solar) with some fossil and biomass CCS • Half of transport final energy from alternatives by 2050 (a mix of electricity, biofuels, and hydrogen) • Large decrease in non-energy emissions from agriculture and land use
Phoenix	• Electricity generation in 2050 dominated by wind, coal CCS, gas without CCS, and hydro • Significant intensity improvements overall and in industry and transport • Low electricity supply requirements owing to demand-side responses • Little fuel switching in transport • Increased emphasis on electrification in industry and buildings after about 2030
TIAM-ECN	• Very large fuel price increases in near and long term (increases greater than in other models for all fuels but oil) • Significant increase in electricity requirements relative to the baseline scenario • Electricity generation in 2050 overwhelmingly based on non-biomass renewables, especially solar (electricity generation becomes a net GHG sink) • Few energy intensity improvements compared to other models • Substantial utilization of biofuels for transport through 2030, then a shift toward hydrogen – over 85% of transport final energy from lower carbon fuels in 2050 • Notable acceleration in electrification of residential and commercial end uses after 2020

Source: CLIMACAP-LAMP (2015).

5. Mitigation costs

Climate policy costs discussed in this section refer to the mitigation effort that Mexico requires to reach its emission reduction targets. It is important to highlight these costs do not include the costs of adaptation, and additionally they do not incorporate the benefits of reaching a stabilization scenario for the country. Therefore, the costs presented in this section should be considered only one part of the equation, that regarding the resources that need to be allocated into mitigation for a given level of emission reduction. The other side of the equation, the benefits of mitigation, is an important area of research outside the scope of this paper.[10]

There are some challenges in comparing cost estimates from models of different structure and coverage of sectors in the economy such as the ones in our model comparison. A comprehensive analysis of the different metrics often used in the analysis of climate change mitigation, both for economy-wide and energy system models, can be found in

[10] Phase 2 of the CLIMACAP-LAMP project will investigate impacts of climate change in Latin America and adaptation policy.

Paltsev and Capros (2013). As explained there, from a social perspective the best measures to assess policy costs are those that estimate the total impact on consumption, since policy makers are usually interested in the appraisal of measures that could affect choices and impose costs on consumers in their national territories. However, since many models cannot estimate overall changes in consumption, other metrics are derived that bear on the specific costs that some sectors could face under mitigation scenarios. For example, since mitigation in the energy sector is critical to reach emission reductions, many models focus on this sector and provide metrics regarding the costs of switches to lower-carbon energy options. While these metrics do not capture important feedbacks and interactions with other sectors of the economy, they are useful indicators for policy makers in charge of energy policy.

Therefore, to discuss the costs of mitigation in Mexico, we structure our analysis as follows. First we present impacts on GDP and changes in consumption that result from the economy-wide models EPPA and Phoenix. Second, we compare the different costs provided by the energy system models, in terms of the total area under the marginal abatement cost curve for POLES and IMAGE, and total additional energy system cost in the case of TIAM-ECN.

5.1. Macroeconomic costs

The two economy-wide models with the capability of capturing macroeconomic effects derived from climate policy are EPPA and Phoenix (both are recursive dynamic CGE models, see Table 3). Both models assume similar growth rates (3.5% and 3.4%, respectively) and compare well in their baseline trajectories (Fig. 12). For the baseline scenario, EPPA estimates Mexico's economy by 2050 will be \$3.6 trillion 2005 USD, compared to Phoenix's \$3.9 trillion estimate. Reaching a 50% reduction in 2050 displaces the growth trend curves downward in both models, as expected (Fig. 12). Both models find a loss of GDP of 1% in 2020 when the policy is first implemented; GDP losses are higher in EPPA thereafter. In 2030, EPPA estimates a GDP loss of 4% compared to 2% in Phoenix and by 2050 EPPA estimates a GDP loss of 15% compared to a 7% GDP loss in Phoenix. In 2050, total GDP loss reported by EPPA is \$526 billion compared to \$292 billion in Phoenix.

Several parameter specifications and calibrations of the models may explain these deviations in total policy cost. First, the models differ in baseline projections. Importantly, Phoenix has higher baseline emissions than EPPA. Other differences in model features also contribute to the cost estimates. Among the more relevant are: a) the vintage structure for capital (EPPA includes capital vintage to account for investment in long-lived assets in some sectors of the economy, such as the power sector); b) different structure of the production functions for electricity, which influences the substitution between technologies within the sector; c) differences in which GHGs and sources of emissions are modeled (EPPA accounts in detail for CO_2 from land-use emissions, cement and bioenergy production, and all GHGs, while the current version of Phoenix does not); d) differences in estimates of total resource endowments in the country (for example the total oil reserves considered and coal, gas, and renewable energy potential); e) differences in the selection of elasticities of substitution between energy sources. A detailed sensitivity analysis to unfold the impact of these parameters is out of the scope of this research, however.

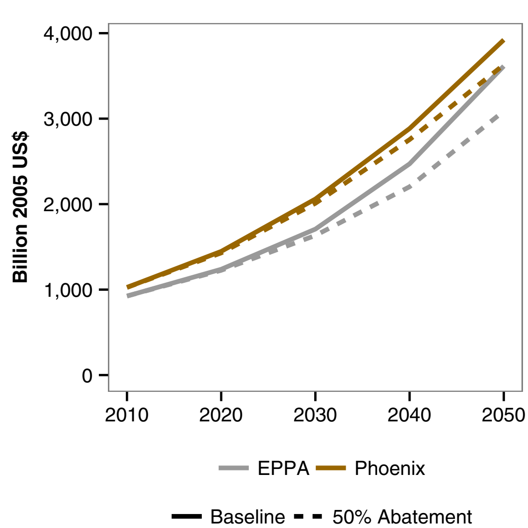

Fig. 12. GDP projections in core baseline and 50% abatement scenarios. Source: CLIMACAP-LAMP (2015).

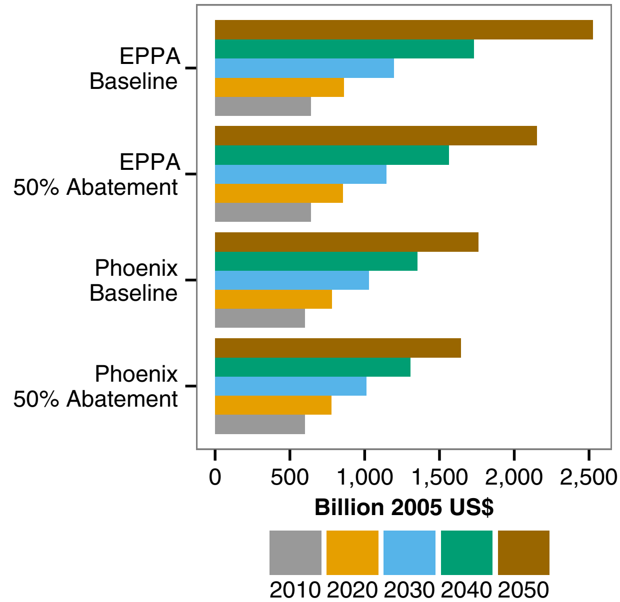

Fig. 13. Consumption in core baseline and 50% abatement scenarios. Source: CLIMACAP-LAMP (2015).

While total GDP loss is a natural metric used for communicating policy costs, economists usually prefer to use consumption or welfare measures, because they relate to the level of total economic wellbeing of the population in each country, and more clearly reflect the economic impact on the population for any given period. Consumption is one of the components of final demand in macroeconomic GDP accounts, with investment, government expenditure, and net trade. Investment in any given period does not contribute to current consumption (it allows future periods' consumption). The net-trade component is affected by movements in terms of trade, and thus requires a separate analysis to evaluate potential losses/gains from trade derived from climate policy. Government expenditure could or could not be productive, and thus it is preferable to consider it also separate from consumption.

Fig. 13 presents the total consumption estimated by the EPPA and Phoenix models, as an indicator of policy costs for Mexico's population. As shown in the figure, both models report reduced consumption as a result of climate policy. Similar to GDP losses, total consumption losses in EPPA are higher than in Phoenix. In 2050, total consumption losses in EPPA are \$375 billion 2005 USD versus \$118 billion in Phoenix. However, the total absolute consumption level is higher in EPPA all through the period, both in the baseline and mitigation cases. In the 50% Abatement scenario, total consumption in EPPA in 2050 is \$2,152 billion 2005 USD versus \$1,643 billion in Phoenix.

5.2. Energy system costs

Energy system models are able to provide estimates for costs of mitigation with different metrics. Because no single metric was available for all of the energy system models in our study, we focus on the area under the marginal abatement cost curve[11] estimate (MAC-area), an indicator provided by POLES and IMAGE, while for TIAM-ECN we use total additional energy system cost. MAC-area costs are shown in Fig. 14. For 2020 and 2030, POLES estimates lower costs than IMAGE (around 60% of the cost of IMAGE); however costs are higher in POLES in the last two decades (POLES costs are higher than those in IMAGE by a factor of two in 2050). This suggests that mitigation options in POLES compared to IMAGE are much cheaper at the beginning, but as stringent targets are imposed, mitigation comes at a much higher cost in POLES. The IMAGE model reports a total annual cost of $4.5 billion 2005 US dollars in 2020, compared to $2.6 billion in the POLES model. By 2050, total annual MAC-area costs are $50 billion and $99 billion for IMAGE and POLES, respectively. These correspond to $41 and $114 per tonne CO_2e reduced in 2050 in these models. It is worth noting that one limitation of the MAC-area method is that it does not capture any of the welfare losses associated with previous distortions in the economy, such as taxes and subsidies to energy, which are relevant in Mexico.

In the case of TIAM-ECN, the metric is not strictly comparable to the rest of the models. This model provides costs as additional total energy system costs. In 2020, TIAM-ECN estimates $53 billion 2005 US dollars per year additional costs for the energy system, in 2030 $263 billion per year, and by 2050 $403 billion per year. The cost per tonne CO_2e reduced in 2050 is $364.

Further areas of research on policy costs could include the evaluation of distributional impacts on different income groups in Mexico as well as the potential to reduce net mitigation costs through pricing carbon and using the revenue to offset distortionary taxes on labor and capital. An interesting question to explore in this context is whether stringent mitigation might induce some energy poverty in the absence of such offsets. All models find that large investment in new energy infrastructure is required, and therefore further studies on capital costs and financing mechanisms could also follow to inform investment decision-making.

5.3. Cost summary

In sum, both macroeconomic models estimate GDP and consumption losses resulting from the 50% Abatement scenario. Considering the range of results from both models, GDP losses in 2020 could be on the order of 1%, in 2030 between 2% and 4%, and in 2050 between 7% and 15%. Consumption also decreases in a similar fashion. By 2050, total consumption losses found by the two models are between $118 and $375 billion 2005 USD per year. The rest of the models provide different metrics to assess costs. POLES and IMAGE find costs in 2050 between $50 and $99 billion 2005 US dollars per year, using the area under the marginal abatement cost curve metric. Finally, TIAM-ECN reports additional total cost for the energy system of $403 billion 2005 US dollars per year in 2050.

It is interesting to compare these numbers to the Mexican government's own assessment of the costs of deep mitigation. In their pivotal 2009 study *The Economics of Climate Change in Mexico*, SEMARNAT and Secretaría de Hacienda y Crédito Público (SHCP) estimate that the cumulative cost of cutting national CO_2 emissions 50% by 2050 would be between .56% and 3.24% of current GDP, depending on the discount rate and assumptions about the cost of carbon (SEMARNAT and SHCP, 2009; the baseline year for emissions is 2002). Taking GDP in 2009 from INEGI (2013), these percentages equate to between about $6 billion and $33 billion 2005 USD—far lower than any of the cost metrics reported by the CLIMACAP-LAMP models. Divergent scenario definitions, discount rates,[12] and assumptions about the availability and costs of demand-side mitigation options likely explain some of the differences between the CLIMACAP-LAMP and SEMARNAT/SHCP findings, although a full accounting of the differences is beyond the scope of this paper.

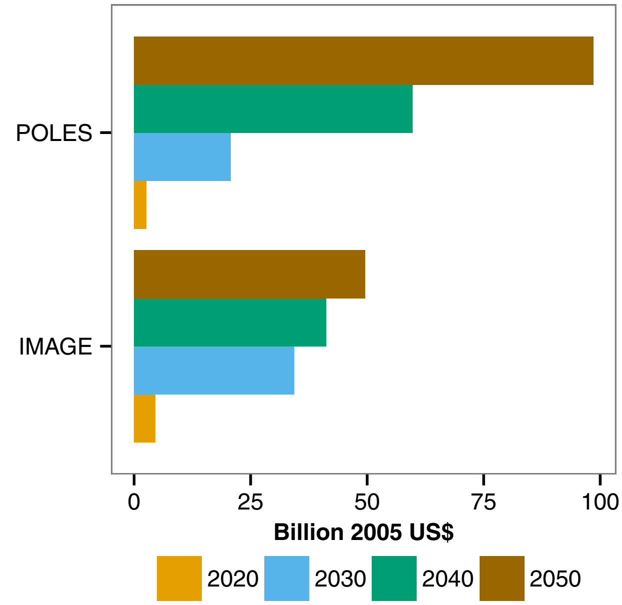

Fig. 14. Total costs as area under marginal abatement cost curve – 50% abatement scenario. Source: CLIMACAP-LAMP (2015).

6. Conclusions

Reversing energy and emission trends in Mexico and cutting national GHG emissions in half by mid-century is an ambitious proposition, one requiring coordinated, sustained action in multiple political, social, and technical domains. Our analysis indicates, however, that it is not a problem with a single dominant solution. The CLIMACAP-LAMP models follow a variety of pathways to deep mitigation for Mexico by 2050, each internally consistent and the product of market activity and optimizing behavior by individuals and firms given reasonable assumptions. As outlined in Section 4, these pathways have important commonalities but differ in substantial ways.

Our results imply that Mexican policy makers have more degrees of freedom than might be supposed as they plan for their 2050 goal. Some paths to deep mitigation do not require wholesale changes in transport fueling infrastructure, for example, and some necessitate little or no improvement in industrial energy intensity compared to the present. While a decarbonized electricity supply does appear to be essential, it could be achieved in several ways, depending on policy priorities and technology availability. A key issue in this context is the long-run outlook for CCS in general and biomass CCS in particular. Many of the models rely on CCS to lower the carbon intensity of electricity in the 50% Abatement scenario, and several use biomass CCS to create new carbon sinks, offsetting emissions in other areas. Although CCS technologies are increasingly well-understood, significant challenges to scaling up their deployment remain, starting with successfully completing large-scale demonstration projects in the power sector (International Energy Agency, 2013). Additional uncertainties surround the potential for leakage of stored CO_2, the regional availability of CO_2 storage capacity, and the shape of the learning curve for CCS (Keppo and van der Zwaan, 2012). If CCS options and costs do not develop as anticipated, CCS-dependent pathways may prove problematic. At the same time, pathways depending on electricity from non-biomass renewables present their own technical challenges, including resource intermittency, energy storage, and transmission and distribution requirements.

Issues like these underscore the importance of another question for Mexican policy makers: how to design a mitigation strategy to be robust

[11] A marginal abatement cost curve relates the quantity of emissions abated with a price level.
[12] The reported costs from the CLIMACAP-LAMP models are not discounted.

across a range of potential futures. The commonalities between the modeled pathways offer some information in this regard, but additional research exploring assumptions and areas of uncertainty in the models would be helpful. A second area where further inquiry is clearly needed concerns policy costs. Our results give some idea of the magnitude of mitigation costs, but the distributional impacts of mitigation policy and the potential to reduce costs through fiscal reform should be examined in more detail. Better assessment of mitigation costs and plans for meeting them, including support from international sources, will only strengthen Mexico's mitigation program. Considering the scope of the country's climate policy, both the Mexican people and the international community have an interest in this outcome.

Acknowledgements

The research that allowed the publication of this paper has been produced with the financial assistance of the European Union in the context of the CLIMACAP project (EuropeAid/131944/C/SER/Multi) and of the U.S. Agency for International Development and U.S. Environmental Protection Agency in the context of the LAMP project (under Interagency Agreements DW89923040 and DW89923951US). The contents of this publication are the sole responsibility of the authors and can in no way be taken to reflect the views of the European Union or the U.S. government. The authors would like to thank all CLIMACAP and LAMP project partners for their feedback and efforts to enable the research results reported in this article.

References

Bouwman, A., Kram, T., Goldewijk, K.K., 2006. Integrated modelling of global environmental change. An Overview of IMAGE 2.4. Netherlands Environmental Assessment Agency.

Clarke, Leon, Jiang, Kejun, Akimoto, Keigo, Babiker, Mustafa, Blanford, Geoffrey, Fisher-Vanden, Karen, Hourcade, Jean-Charles, et al., 2014. Assessing transformation pathways. In Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (http://report.mitigation2014.org/drafts/final-draft-postplenary/ipcc_wg3_ar5_final-draft_postplenary_chapter6.pdf).

CLIMACAP-LAMP, 2015. CLIMACAP-LAMP scenario database. https://tntcat.iiasa.ac.at/CLIMACAP-LAMPDB/ (Accessed 29 September 2014).

Climate and Clean Air Coalition to Reduce Short Lived Climate Pollutants, 2014. Definitions: short-lived climate pollutants. http://www.unep.org/ccac/Short-LivedClimatePollutants/Definitions/tabid/130285/Default.aspx (Accessed 11 August 2014).

Collins, M., Knutti, R., Arblaster, J., Dufresne, J.L., Fichefet, T., Friedlingstein, P., Gao, X., et al., 2013. Long-term climate change: projections, commitments and irreversibilit. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge (http://www.climatechange2013.org/images/report/WG1AR5_Chapter12_FINAL.pdf).

Consejo Nacional de Población, 2014. Datos de proyecciones. http://www.conapo.gob.mx/es/CONAPO/Proyecciones_Datos (Accessed 24 June 2014).

European Commission, 2011. Joint Research Centre/PBL Netherlands Environmental Assessment Agency. http://edgar.jrc.ec.europa.eu/overview.php?v=GHGts1990-2010 (Accessed 23 June 2014).

Federal Government of Mexico, 2013. National climate change strategy: 10–20-40 vision. http://www.encc.gob.mx/en/download.php?file=ENCC_EnglishVersion.pdf (Accessed 30 April 2014).

Instituto Nacional de Estadística y Geografía, 2013. Sistema de cuentas nacionales de México. http://www.inegi.org.mx/sistemas/bie/ (Accessed 17 April 2014).

Instituto Nacional de Estadística y Geografía, 2014. Banco de información INEGI - población total. http://www3.inegi.org.mx/sistemas/biinegi/ (Accessed 17 April 2014).

International Energy Agency, 2013. Technology roadmap: carbon capture and storage. http://www.iea.org/publications/freepublications/publication/TechnologyRoadmapCarbonCaptureandStorage.pdf.

International Monetary Fund, 2014. World economic outlook database. http://www.imf.org/external/pubs/ft/weo/2014/02/weodata/index.aspx (Accessed 10 April 2015).

Keppo, Ilkka, van der Zwaan, Bob, 2012. The impact of uncertainty in climate targets and CO2 storage availability on long-term emissions abatement. Environ. Model. Assess. 17 (no. 1–2), 177–191. http://dx.doi.org/10.1007/s10666-011-9283-1 (April).

Kitous, A., Criqui, P., Bellevrat, E., Chateau, B., 2010. Transformation patterns of the worldwide energy system–scenarios for the century with the POLES model. Energy J. 31 (no. Special Issue 1 on The Economics of Low Stabilization), 57–90.

Kober, T., van der Zwaan, B., Rösler, H., 2014. Emission certificate trade and costs under regional burden-sharing regimes for a 2 °C climate change control target. Clim. Change Econ. 05 (01), 1440001. http://dx.doi.org/10.1142/S2010007814400016.

Kober, Tom, Falzon, James, van der Zwaan, Bob, Calvin, Kate, Kanudia, Amit, Kitous, Alban, Labriet, Maryse, 2016. A multi-model study of energy investments in Latin America under climate control policy". Energy Econ. 56, 543–551 (in this issue).

Kriegler, Elmar, Weyant, John P., Blanford, Geoffrey J., Krey, Volker, Clarke, Leon, Edmonds, Jae, Fawcett, Allen, et al., 2014. The role of technology for achieving climate policy objectives: overview of the EMF 27 study on global technology and climate policy strategies. Clim. Chang. 123 (no. 3–4), 353–367. http://dx.doi.org/10.1007/s10584-013-0953-7.

Nachmany, M., Fankhauser, S., Townshend, T., Collins, M., Landesman, T., Matthews, A., Pavese, C., Rietig, K., Schleifer, P., Setzer, J., 2014. The GLOBE Climate Legislation Study: A Review of Climate Change Legislation in 66 Countries. Fourth *edition*. GLOBE International and the Grantham Research Institute, London School of Economics, London (http://www.globeinternational.org/studies/legislation/climate).

Paltsev, S., Capros, P., 2013. Cost concepts for climate change mitigation. Clim. Change Econ. 4 (Suppl. 01).

Paltsev, S., Reilly, J.M., Jacoby, H.D., Eckaus, R.S., McFarland, J.R., Sarofim, M.C., Asadoorian, M.O., Babiker, M.H., 2005. The MIT Emissions Prediction and Policy Analysis (EPPA) Model: Version 4. Technical Report. MIT Joint Program on the Science and Policy of Global Change.

Rösler, Hilke, van der Zwaan, Bob, Keppo, Ilkka, Bruggink, Jos, March 2014. Electricity versus hydrogen for passenger cars under stringent climate change control. Sustainable Energy Technol. Assess. 5, 106–118. http://dx.doi.org/10.1016/j.seta.2013.11.006.

Secretaría de Energía, 2014a. Sistema de información energética - balance nacional de energía: balances por producto. http://sie.energia.gob.mx/ (Accessed 16 July 2014).

Secretaría de Energía, 2014b. Sistema de información energética - balance nacional de energía: consumo de energía en el sector agropecuario. http://sie.energia.gob.mx/ (Accessed 16 July 2014).

Secretaría de Energía, 2014c. Sistema de información energética - balance nacional de energía: consumo de energía en el sector industrial. http://sie.energia.gob.mx/ (Accessed 16 July 2014.).

Secretaría de Energía, 2014d. Sistema de información energética - balance nacional de energía: consumo de energía en el sector transporte. http://sie.energia.gob.mx/ (Accessed 16 July 2014).

Secretaría de Energía, 2014e. Sistema de información energética - balance nacional de energía: consumo de energía en los sectores residencial, comercial y público. http://sie.energia.gob.mx/ (Accessed 17 July 2014).

Secretaría de Energía, 2014f. Sistema de información energética - balance nacional de energía: consumo final de energía por sector. http://sie.energia.gob.mx/ (Accessed 18 April 2014).

Secretaría de Energía, 2014g. Sistema de información energética - balance nacional de energía: consumo nacional de energía por rubro. http://sie.energia.gob.mx/ (Accessed 25 June 2014).

Secretaría de Energía, 2014h. Sistema de información energética - sector eléctrico: generación bruta de energía por tecnología. http://sie.energia.gob.mx/ (Accessed 1 August 2014).

Secretaría de Gobernación, 2014. Ley de la industria eléctrica. http://dof.gob.mx/nota_detalle.php?codigo=5355986&fecha=11/08/2014 Accessed 13 April 2015.

Secretaría de Medio Ambiente y Recursos Naturales, 2012. General law on climate change. http://www.encc.gob.mx/en/documentos/general-climate-change-law.pdf (Accessed 30 April 2014).

Secretaría de Medio Ambiente y Recursos Naturales, 2013. Resumen del inventario nacional de emisiones de gases de efecto invernadero. http://dgeiawf.semarnat.gob.mx:8080/ibi_apps/WFServlet?IBIF_ex=D3_AIRE02_01&IBIC_user=dgeia_mce&IBIC_pass=dgeia_mce (Accessed 16 April 2014).

Secretaría de Medio Ambiente y Recursos Naturales, Secretaría de Hacienda y Crédito Público, 2009. *The economics of climate change in Mexico: synopsis*. http://biblioteca.semarnat.gob.mx/janium/Documentos/Cecadesu/Libros/Economics%20of%20climate%20change.pdf (Accessed 13 April 2015).

Sue Wing, I., Daenzer, K., Vanden, K.F., Calvin, K., 2011. Phoenix Model Documentation".

van der Zwaan, B.C.C., Calvin, K., Clarke, L., 2016. Climate mitigation in Latin America: implications for energy and land use. Introduction to the special issue on the findings of the CLIMACAP-LAMP project. Energy Economics 56, 495–498 (in this issue).

van der Zwaan, Bob, Keppo, Ilkka, Johnsson, Filip, 2013. How to decarbonize the transport sector? Energy Policy 61, 562–573. http://dx.doi.org/10.1016/j.enpol.2013.05.118 (October).

van Ruijven, Bas, Daenzer, Katie, Fisher-Vanden, Karen, Kober, Tom, Paltsev, Sergey, Beach, Robert, Calderon, Silvia, et al., 2016. Baseline projections for Latin America: base-year assumptions, key drivers and greenhouse gas emissions. Energy Econ. 56, 499–512 (in this issue).

Wise, M., Calvin, K., 2011. GCAM 3.0 Agriculture and Land Use: Technical Description of Modeling Approach. Pacific Northwestern National Laboratory.