Energy Economics 56 (2016) 575–586

Contents lists available at ScienceDirect

Energy Economics

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

Achieving CO_2 reductions in Colombia: Effects of carbon taxes and abatement targets

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ARTICLE INFO

Article history:
Received 21 August 2014
Received in revised form 19 May 2015
Accepted 26 May 2015
Available online 3 June 2015

JEL classification:
H23
Q40
Q54
C61
C68
O57

Keywords:
Climate change mitigation
Carbon taxes
CO_2 abatement targets
Energy modeling

ABSTRACT

In this paper we investigate CO_2 emission scenarios for Colombia and the effects of implementing carbon taxes and abatement targets on the energy system. By comparing baseline and policy scenario results from two integrated assessment partial equilibrium models TIAM-ECN and GCAM and two general equilibrium models Phoenix and MEG4C, we provide an indication of future developments and dynamics in the Colombian energy system. Currently, the carbon intensity of the energy system in Colombia is low compared to other countries in Latin America. However, this trend may change given the projected rapid growth of the economy and the potential increase in the use of carbon-based technologies. Climate policy in Colombia is under development and has yet to consider economic instruments such as taxes and abatement targets. This paper shows how taxes or abatement targets can achieve significant CO_2 reductions in Colombia. Though abatement may be achieved through different pathways, taxes and targets promote the entry of cleaner energy sources into the market and reduce final energy demand through energy efficiency improvements and other demand-side responses. The electric power sector plays an important role in achieving CO_2 emission reductions in Colombia, through the increase of hydropower, the introduction of wind technologies, and the deployment of biomass, coal and natural gas with CO_2 capture and storage (CCS). Uncertainty over the prevailing mitigation pathway reinforces the importance of climate policy to guide sectors toward low-carbon technologies. This paper also assesses the economy-wide implications of mitigation policies such as potential losses in GDP and consumption. An assessment of the legal, institutional, social and environmental barriers to economy-wide mitigation policies is critical yet beyond the scope of this paper.

1. Introduction

To lower greenhouse gas (GHG) emissions in Latin America and the Caribbean, the focus historically has been on lowering the emissions of the region's large emitters, such as Mexico and Brazil. Less attention has been paid to countries like Colombia because of its small contribution to regional and global emissions. In 2005, Colombia contributed approximately 0.35% to global and 3.4% to Latin American GHG emissions, despite contributing 6% to the region's Gross Domestic Product (GDP) (Joint Center Research, 2010).

Colombia's comparably small share of total GHG emissions in Latin America is largely the result of its low energy consumption and high clean electricity production relative to many other Latin American countries. Energy use in Colombia was 1.34 EJ in 2010, which is small compared to other Latin American countries with economies of similar size; e.g., Chile (UPME, 2014; World Bank, 2014a,b). For the past decade, hydropower has remained the main source of electricity generation in Colombia, comprising 76% of total electricity generation (UPME, 2014). Energy consumed in the transportation sector is almost entirely fossil fuel based, with gas and electricity comprising 68% of total energy consumed by the sector (UPME, 2014).

In 2004, Colombia emitted approximately 180 million tons of GHG, consisting of CO_2 (50%), CH_4 (30%), N_2O (19%), and other gases (1%). Agriculture, land use, land use change and forestry were the largest source of GHG emissions (52% of total emissions), followed by energy (37%),[1] waste (6%), and industrial processes (5%). Fig. 1 provides a breakdown of the sources of Colombia's emissions in 2004 (IDEAM, 2009).

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[1] According to the Inventory 31% of total emissions come from fossil fuel combustion.

http://dx.doi.org/10.1016/j.eneco.2015.05.010

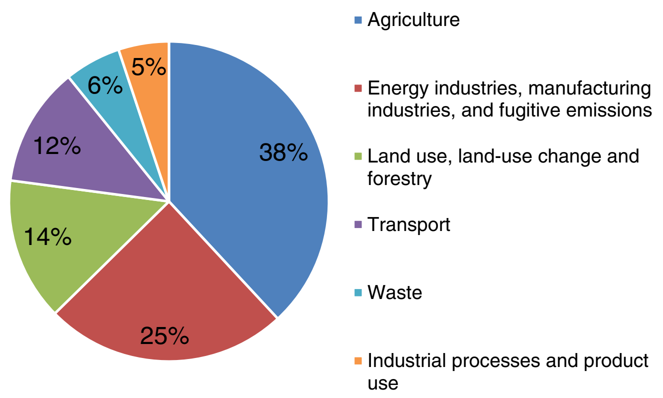

Fig. 1. GHG emissions by sector in Colombia in 2004.

Colombia's current low carbon economy may not be sustainable due to the country's economic growth and shifts in the energy mix. The Colombian economy has experienced steady growth over the past decade, with an average annual growth of GDP per capita of 3.5% from 2005 to 2012, above the Latin American average (FMI, 2013). Higher income has increased the demand for fossil fuels, especially in the transportation, manufacturing, and power generation sectors. The use of fossil fuels for electricity generation still remains low; however, natural gas has gained prominence in the past decade (World Bank, 2014b). Furthermore, Colombia has a substantial coal resource base with reserves expected to last 92 years at current production levels (MME-UPME, 2012). The use of coal, therefore, may increase in a future with low energy prices and reductions in water resources due to climate change. Thus, the potential for large increases in Colombia's carbon emissions in the future means that a renewed focus on efforts to reduce GHG emissions in Colombia may be needed.

The development of climate policy in Colombia is still in its initial stages. A low carbon development strategy is currently being drafted which aims at designing and implementing plans, projects and policies that promote the mitigation of GHG emissions without compromising social and economic growth in Colombia. The strategy has yet to consider the use of economic instruments such as carbon taxes and abatement targets to achieve these goals.

The purpose of this paper is to explore the implications of alternative CO_2 emission scenarios for Colombia's economy and energy system. These scenarios, developed within the CLIMACAP-LAMP project, include scenarios where GHG reductions are achieved through the implementation of carbon taxes or abatement targets. More information on scenario specifications, model descriptions, overall project description and information on the topics of other papers included in this Special Issue can be found in B. van der Zwaan et al. (2016a) and B.C.C. van der Zwaan et al. (2016b).[2]

Scenarios for Colombia were constructed using four models: two integrated assessment, partial equilibrium models—the Global Change Assessment Model (GCAM), and the TIMES Integrated Assessment Model of the Energy Research Center of the Netherlands (TIAM-ECN)—and two Computable General Equilibrium models (CGE)—the Phoenix model and *Modelo de Equilibrio General Computable de Cambio Climático para Colombia* (MEG4C).

These models identify Colombia as a single region rather than one part of a more aggregate region, which allows us to examine the implications of these alternative scenarios for Colombia specifically. The results in this paper include the impacts on the Colombian economy from the implementation of carbon taxes and abatement targets; however when analyzing the effect on emissions we only focus on CO_2 to allow for comparability between models, as not all models represent the suite of GHG emissions. Additionally, the MEG4C model, at its current stage of development, only generates results on the economic costs of policy and not implications for the energy system.

The paper is organized as follows. Section 2 describes the modeling framework used in the analysis while Section 3 provides the baseline trajectories of CO_2 emissions used in the modeling exercise. Section 4 presents the emission trajectories implied by the carbon tax and carbon-constraint scenarios and Section 5 examines the potential economic costs of implementing these policy instruments. Lastly, Section 6 offers some concluding remarks, including implications for Colombia's climate change mitigation policy.

2. Modeling framework

The approach used in this paper to understand the implications of alternative emission scenarios for Colombia's economy is to conduct an intercomparison of results from four participating models that represent Colombia as a separate country. Each model generates results for a suite of common scenarios, including one baseline scenario and three climate policy scenarios. By identifying systematic similarities and differences between the models, we construct plausible storylines from the models about the energy economy's response to climate policy in Colombia. This section describes key characteristics of each participating model, including a comparison of data sources and assumptions across models, and provides an overview of the CLIMACAP-LAMP project scenarios used in the model intercomparison.

2.1. Model descriptions

The Global Change Assessment Model (GCAM) is a global integrated assessment model, combining representations of the economy, energy system, agriculture, land use, and climate change (Clarke et al., 2007; Thomson, 2011). The model is a dynamic recursive, partial equilibrium model that adjusts prices until supply and demand balances for all energy and agricultural markets. The model operates in five-year time steps from 1990 to 2100 and comprises 32 regions of the world. Primary energy reserves are based on Rogner (1997) and energy resources are assumed to be fairly abundant which, along with assumed technological progress, results in lower growth in extraction cost due to resource depletion. Substitution across energy types in production is driven by relative cost differences, and a logit formulation is employed to avoid a winner-take-all result. In the model, coal, gas, oil and biomass are traded globally.

The TIAM-ECN model (Rösler et al., 2014; van der Zwaan et al., 2013) is designed for long-term energy systems and climate policy analysis. The model is global in scope with a world energy system disaggregated into 20 distinct regions. TIAM-ECN is a linear optimization model, based on energy system cost minimization with perfect foresight until 2100. The model simulates the development of the global energy economy over time from resource extraction to final energy use. The objective function is defined as the discounted total energy system costs summed over all time periods and across all regions. The main cost components included in the objective function are investment costs and fixed plus variable operation and maintenance costs for the various energy supply and demand options, including emission reduction measures. TIAM-ECN is a partial equilibrium model with exogenous demands for energy services. The model utilizes a comprehensive technology database that includes a number of fuel transformation and energy supply pathways encompassing the set of possible fossil, nuclear, and renewable energy technologies.

Phoenix is a dynamic recursive, computable general equilibrium (CGE) model calibrated to the GTAP 7 database (Sue Wing et al., 2011). The model solves in 5-year time steps from 2005 through 2100 and comprises twenty-six regions. The regional identities include both individual countries (e.g. USA, Brazil, and Canada) and aggregates of countries within a particular geographic region (e.g. Middle East, North Africa, and the European Union). The economies of each region comprise 21 material and services sectors and 5 energy sectors. Since the model is general

[2] More information on the CLIMACAP-LAMP project and the database used for this paper are available at: https://tntcat.iiasa.ac.at/CLIMACAP-LAMPDB/.

Table 1
Base year, data sources and structural differences between models.

Model/feature	GCAM	TIAM-ECN	Phoenix	MEG4C
Economic coverage and feedback	Partial equilibrium	Partial equilibrium	General equilibrium	General equilibrium
Foresight and dynamics	Myopic/recursive	Inter-temporal Optimization	Myopic/recursive	Myopic/recursive
Calibrated years	1990, 2005, 2010	2005, 2010	2004	2005
Endogenous variables	Prices, energy supply, energy demand, emissions	Energy supply, trade, emissions, prices (marginal costs)	Prices, energy supply, energy demand, emissions, final consumption, GDP	Prices, emissions, GDP, final consumption
Exogenous variables	Population, labor productivity, technology cost, resource availability	End-use demand (population, GDP), technology parameters (investment costs, etc)	Population, labor productivity, AEEI growth rates	Population, emissions factors
Emissions data sources	CDIAC, EDGAR	EDGAR, IEA	CDIAC	CLCDS
Population data sources	UN	UN	UN	DANE
GDP data sources	UN, WB	WB	GTAP, PWT	MHCP
Energy data sources	IEA	IEA	IEA, GTAP	UPME

CDIAC Carbon Dioxide Information Analysis Center. EDGAR Emissions Database for Global Atmospheric Research. UN United Nations. WB world bank. IEA International Energy Agency. GTAP Global Trade Analysis Project. PWT Penn World Table. CLCDS Colombia's Low Carbon Development Strategy. DANE National Administrative Department of Statistics. MHCP Ministry of Finance and Public Credit. UPME Mining and Energy Planning Unit.

equilibrium, each sector of the economy is represented: producers minimize cost given a particular nested constant elasticity of substitution (CES) production technology and consumers maximize utility given a budget constraint and a nested CES utility function based on consumption. A set of prices is determined to clear the markets. After each period, capital, labor, the autonomous energy efficiency improvement (AEEI) parameters, and energy reserve data are updated, with labor productivity and AEEI growth rates set exogenously. Production is modeled as a nested CES function with energy inputs in one nest, materials in another nest, and value added (capital and labor) in another. Energy and materials are substitutes and the combined energy-materials nest substitutes with the value added nest. The elasticity of substitution between inputs is determined during calibration. With respect to trade, crude oil and gas are traded as Heckscher–Ohlin goods, which assumes that imported and domestic supplied goods are perfect substitutes. The remaining material and energy commodities are traded as Armington goods, which assumes that imported and domestic supplied goods are imperfect substitutes.

MEG4C is a recursive-dynamic CGE model developed to analyze the economic impacts of climate change and mitigation policies in Colombia (SDAS-DNP, 2012). The model is based on the GREEN model (General Equilibrium Environmental Model) developed by the OECD to study the effects of policies to reduce GHG emissions (Burniaux et al., 1992). Similar to the Phoenix model, all agents of the economy are represented, with consumers maximizing utility and firms maximizing profits, and prices are determined to clear the markets. The MEG4C model comprises 15 sectors, two of which are energy, and four agents: households, firms, the government and the external sector. The model is calibrated using data from official Colombian government sources.

2.2. Data sources and assumptions

Differences in model results can be explained, in part, by differences in base years, sources of information and unique features of the models' structures. Table 1 summarizes general differences between models used in this analysis. For further details on the models, particularly with respect to differences in baseline assumptions and energy technology deployment, we refer to B. van der Zwaan et al. (2016a), B.C.C. van der Zwaan et al. (2016b) and van Ruijven et al. (2016).

2.3. Climate policy scenarios

The scenarios used in this analysis follow the CLIMACAP-LAMP project protocol, further described in B. van der Zwaan et al. (2016a), B.C.C. van der Zwaan et al. (2016b). Each modeling team was asked to run three climate policy scenarios which were compared to a baseline scenario that assumes the absence of climate policy. By comparing CO_2 emission across scenarios, we are able to assess how emissions may deviate from their baseline levels through the implementation of carbon taxes and abatement targets over the period 2020–2050. Table 2 describes the scenarios used in the analysis.

3. Baseline scenario

Our analysis begins with a comparison of the baseline scenario results. A close examination of baseline trajectories is important for a number of reasons. For one, to assess the economic impact of climate policies, we must measure the difference between results from the climate policy scenario and a "business as usual" or "no policy" scenario. Therefore, baseline scenario results provide the basis for comparison with climate policy scenarios. Another important aspect of a baseline scenario intermodel comparison is that it would elucidate important structural differences between models that can help explain differences in climate policy scenario results.

Fig. 2 provides the baseline scenario trajectories of CO_2 emissions for Colombia from 2005 to 2050 generated by each of the four models. In general, all models project an increase in emissions until 2050, with no stabilization achieved over this period. The difference in emissions between models grows over time, with MEG4C projecting the highest growth in emissions and TIAM-ECN the lowest. This variation in baseline emission trajectories across models is due to differences in model assumptions and characteristics as discussed previously. In order to identify the major factors influencing these emission trajectories, we conduct a decomposition analysis to assess how the drivers of emissions evolve in each model.

3.1. Decomposition of drivers of CO_2 emissions

To understand what is driving the growth in emissions over time, it is useful to decompose the relative contribution of the factors of the Kaya identity (Kaya and Yokobori, 1997), namely population, GDP per capita, energy intensity of GDP, and the carbon intensity of energy:

$$C = P \times \frac{Q}{P} \times \frac{E}{Q} \times \frac{C}{E}$$

where

C ≡ Carbon emissions (Mt CO_2)
P ≡ Population (Million)
Q ≡ GDP (Billion US$2005)
E ≡ Final energy use (EJ)[3]

[3] Typically primary energy is used in the Kaya identity, however not all of the models report this. Instead final energy was used.

Table 2
Baseline and policy scenarios.

Scenario	Scenario description
Core baseline	Business-as-usual scenario including climate and energy policies enacted prior to 2010.
High CO_2 price	A carbon tax of 50 \$/tCO_2e is levied in 2020, growing at 4%/year to reach 162\$/tCO_2e in 2050.
50% abatement (GHG)	GHG emissions, excluding LUC CO_2, are reduced by 12.5% from 2010 levels by 2020, linearly increasing to 50% of 2010 levels by 2050.
50% abatement (FF&I)	Fossil fuel and industrial CO_2 emissions are reduced by 12.5% from 2010 levels by 2020, linearly increasing to 50% of 2010 levels by 2050.

Population and GDP per capita growth were not harmonized across models in an effort to explore some of the uncertainties in future pathways for Colombia. However, the variation in pathways shown in this paper should be seen as representing the full uncertainty range across the models. For a more detailed discussion of these drivers, see B. van der Zwaan et al. (2016a) and B.C.C. van der Zwaan et al. (2016b).

Population projections, shown in panel (a) of Fig. 3, exhibit a declining growth rate over time, although the peak in population is not reached before 2050. In terms of GDP per capita shown in panel (b), MEG4C and Phoenix are more optimistic projecting that by 2050 the country's mean income will be above \$14,000, whereas GCAM and TIAM-ECN are more conservative with figures close to \$10,000. As population projections are similar between models, the differences in income per capita projections are therefore due to differences in projected GDP growth rates across models.

Projected energy and carbon intensities over time in the baseline scenario vary across models. Most models project a declining energy intensity of GDP over time, but projected carbon intensities of energy diverge. To understand these differences across models, it is important to examine the dynamics of the energy system represented in each model.

As shown in panel (c) of Fig. 3, the energy intensity of GDP, defined as final energy consumed per unit of output, is falling in the projections of the Phoenix, GCAM and TIAM-ECN models. These projections are consistent with historic trends and underscore the potential for further energy efficiency improvements and shifts in the composition of the economy toward less energy intensive sectors, such as services, in the future. In the projections of the Phoenix model, this decline is the result of exogenous assumptions regarding autonomous energy efficiency improvements (AEEI) over time which are based on International Energy Agency (IEA) forecasts (Sue Wing, et al., 2011) and to a lesser extent on the endogenous substitution of capital and labor for energy. In the case of GCAM and TIAM-ECN, this decline is an endogenous result of the adoption of new, more efficient end-use technologies. The rate of efficiency and other performance improvements for these technologies are exogenously specified.

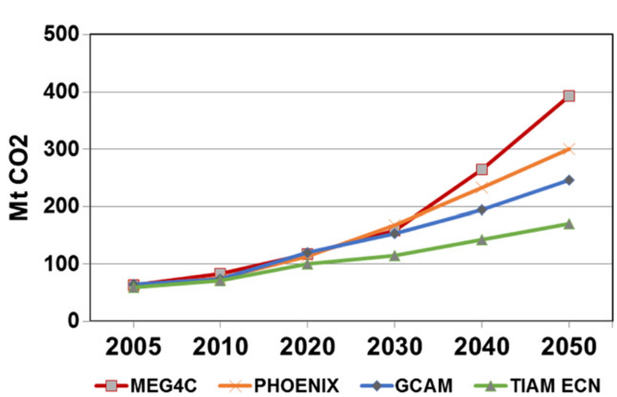

Fig. 2. CO_2 emissions in Colombia.

The MEG4C model, on the other hand, projects increasing energy intensity in the country over time. This is a counterintuitive result which is largely due to the fact that MEG4C is not calibrated using projections of future energy efficiency improvements in Colombia from outside sources. In MEG4C, economic growth is calibrated by changing the capital productivity parameter. As a result, capital intensive sectors, such as energy, are able to increase production at lower relative prices, leading to a fall in the relative price of energy by 6.5% over the period 2005–2050.[4] These lower energy prices stimulate higher demand for energy, causing energy consumption to grow faster than GDP which results in an increase in energy intensity over time.

Differences across models are more profound in the case of carbon intensity trends. As shown in panel (d) of Fig. 3, GCAM and Phoenix project rising carbon intensities of energy over time. In both models, this outcome is explained by an increase in thermal electric generation (mainly natural gas and coal) as a share of total electricity generation, which leads to an increase in the consumption of carbon-based fuels by the electricity sector. This is evident in panels (a) and (c) of Fig. 4 where the use of natural gas in electricity generation is increasing over time in the case of GCAM, and the use of coal is increasing in the case of Phoenix. These models show that even with increasing extraction costs, fossil fuels, and in particular coal, will be a relatively inexpensive source of energy compared to non-hydro renewables in the absence of climate policies. Furthermore, the use of fossil fuels will increase as electricity demand increases over time and hydropower potential reaches its limit, which in GCAM is 0.21 EJ/yr by 2050. In GCAM, natural gas and coal take a more prominent role in the energy system, whereas in Phoenix, coal becomes the dominant source of energy in electricity generation over time. Moreover, in both models, wind and solar expansion is limited due to inherent problems of intermittent supply and storage associated with renewables.

The TIAM-ECN and MEG4C models both project declines in the carbon intensity of energy as seen in panel (d) of Fig. 3. In the case of TIAM-ECN, this is the result of a decline in carbon intensity in both the residential and transport sectors. In the residential sector, households shift to greater electricity use due to an increase in the adoption of information and communication technologies and other electric household appliances such as air conditioning. Electricity production remains less carbon intensive than in GCAM and Phoenix due to further deployment of Colombia's hydropower as shown in panel (b) of Fig. 4. In the transport sector, the carbon intensity of energy decreases as a result of the adoption of more efficient engines, particularly for freight transportation.

Finally, the MEG4C model incorporates emission coefficients from Colombia's Low Carbon Development Strategy, which projects a declining trend until 2040 and is linearly extrapolated to 2050. The decrease in carbon intensity in the baseline scenario reflects predicted changes in the input mix of the energy intensive sectors, such as transportation and industry. Freight and public transportation are assumed to adopt Euro IV and V standards,[5] where the former assumes an increase in the use of natural gas. In MEG4C's baseline scenario, the share of electric vehicles also increases. As for industry, activities such as cement production substitute biomass for coal to meet its required energy standard.

In summary, this section presented potential trajectories of CO_2 emissions from 2005 to 2050 for Colombia in a baseline scenario without climate policy. Decomposing the main drivers of economy-wide emissions using the Kaya identity, we find that even though models project different CO_2 emission trajectories for Colombia, increasing GDP per capita, population growth and carbon intensity lead to higher emissions, regardless of the trend in energy intensity. Increasing carbon

[4] By comparison, in Phoenix the relative price of energy increases 39% from 2005 to 2050.

[5] Euro IV and V standards are part of the European Union's heavy duty emissions regulation.

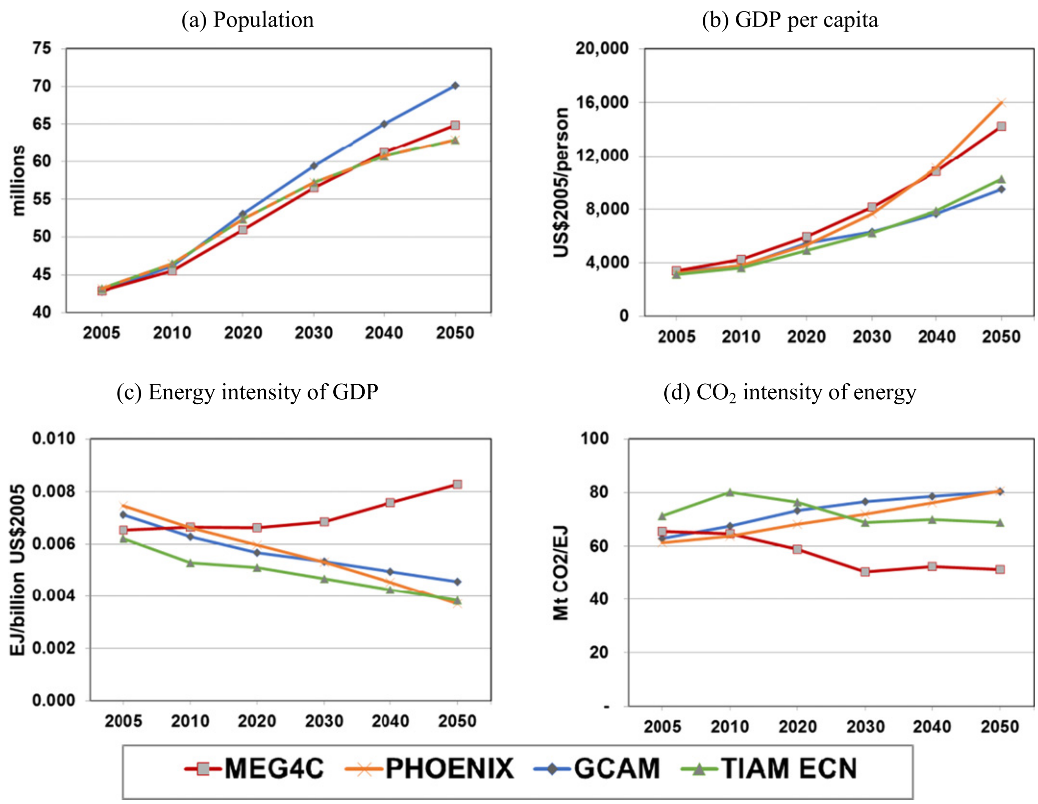

Fig. 3. Components of the Kaya identity.

intensity of energy in the country is driven by an increased use of carbon-emitting technologies in the electric power sector. Generation from coal and natural gas grows to meet most new demand without significant hydropower expansion. On the other hand, emission growth could be lower over time if Colombia maintains its share of hydropower generation while deploying energy efficient technologies in the other

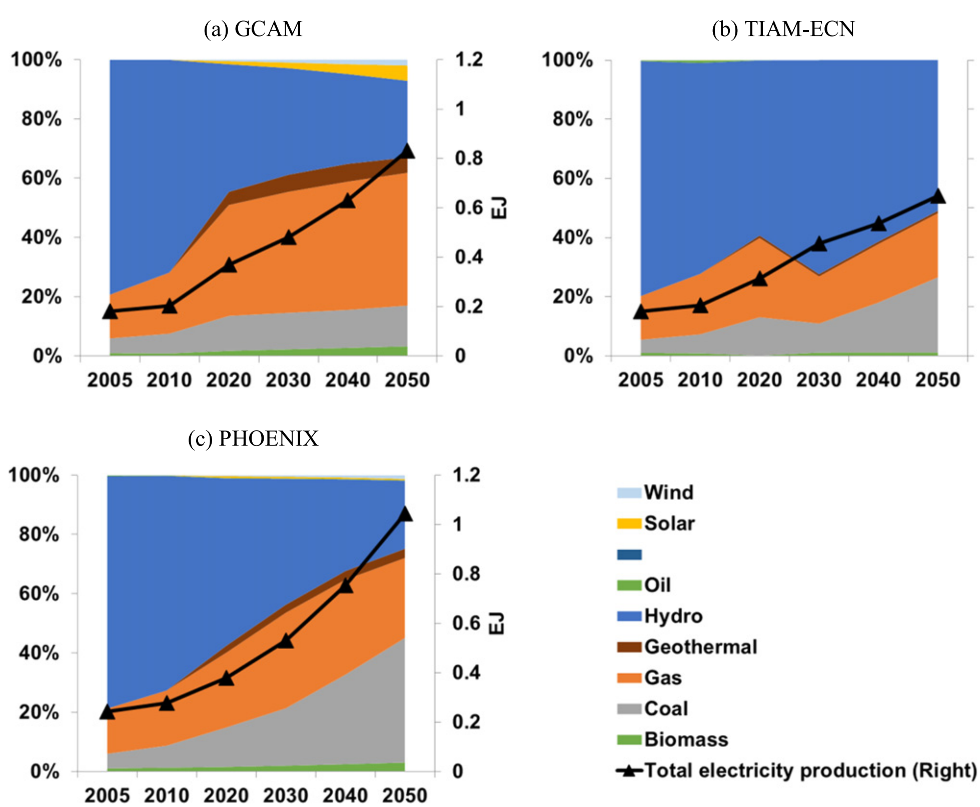

Fig. 4. Composition and total electricity generation by fuel in the baseline scenario.

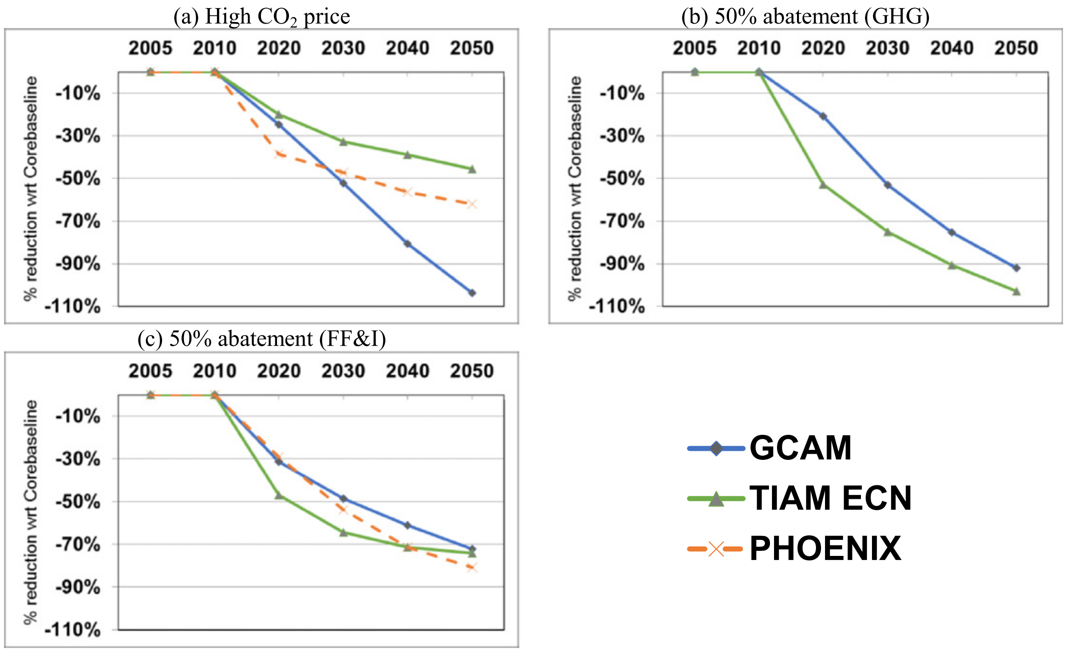

Fig. 5. CO_2 abatement with respect to baseline.

major energy consuming sectors such as the residential, transportation and industrial sectors.

4. Carbon tax and abatement target scenarios

Carbon taxes and emission trading systems are considered the most cost-effective carbon pricing instruments to reduce emissions (OCDE, 2013). In this section, we evaluate the potential for CO_2 emission reductions from the implementation of the policy scenarios described in Table 2. We begin by presenting the overall effect on the trajectory of CO_2 emissions from the implementation of each of these policies. We then describe differences in the impacts on the energy system between three of the models (TIAM-ECN, GCAM and Phoenix). MEG4C is not included in this section of the analysis because the model does not currently report the effects of climate policy on the energy system.

4.1. Effects of carbon tax and abatement targets on CO_2 emissions

The model results show that significant levels of CO_2 abatement may be achieved through taxes and emission targets. Fig. 5 shows emission reductions from baseline levels in the three policy scenarios. Phoenix is not included in our analysis of the 50% abatement of GHG scenario in this and the following sections, since this model does not include non-CO_2 GHG emissions.

Panel (a) in Fig. 5 shows that the $50/t$CO_2$ tax scenario results in CO_2 emissions in 2050 that are lower than 2050 emissions in the baseline scenario by 45% in TIAM-ECN and by 104% in GCAM. Large emission reductions in GCAM are achieved through the deployment of carbon capture and storage (CCS) technology in coal, gas and biomass. This assumes that Colombia has access to approximately 92 GtCO_2 of on-shore storage at $75 per ton of CO_2, and that overnight capital costs for a biomass plant is $2300 compared to $1800 for a non-CCS biomass electricity plant.

Despite the differences in abatement levels, both TIAM-ECN and GCAM achieve the emission reductions by limiting fossil fuel combustion, though some portion of this is obtained through emission reductions in upstream fossil fuel production, agriculture, and land use change. In GCAM, however, there is a limit to the amount of non-CO_2 emissions that can be reduced, as this model is more pessimistic about the ability to reduce CH_4 and N_2O in the agricultural sectors.

When comparing the $50/t$CO_2$ tax vis-à-vis the 50% GHG abatement target for TIAM-ECN, (panels (a) and (b) of Fig. 5), the abatement target achieves higher reductions in CO_2 emissions than the tax, which is consistent with a higher carbon permit price. In contrast, the emission results from GCAM are similar in each of the scenarios, implying similar implicit prices.[6]

Panels (b) and (c) of Fig. 5 provide a comparison of the 50% abatement scenarios which shows that greater reductions are achieved in both TIAM-ECN and GCAM with a cap on all GHG than with only a cap on CO_2 emissions from FF&I.

The difference in abatement between scenarios is better understood by analyzing the effects of these policies on the energy system, where carbon prices motivate the deployment of new energy sources or technologies. The following section explores the effects of taxes and abatement targets on primary energy, electricity production, and final energy demand in Colombia.

4.2. Effects of carbon taxes and abatement targets on the energy system

In this section, we compare the results across models for each of the policy scenarios. Despite differences between the models and scenarios, which provide an indication of the uncertainties surrounding the implications of future climate policies, there are some robust conclusions to be drawn from a model-scenario-comparison. For example, in all three climate policy cases, the penetration of alternative cleaner energy sources and technologies, as a share of total primary energy supply, grows significantly as seen in Fig. 6. For instance, as shown in panel (a), by 2050, the GCAM model projects the share of biomass in total primary energy to grow from 12% in the baseline scenario, to 40% in the 50% GHG abatement scenario. This increase is due to the deployment of CCS with biomass, which as a share of primary energy, grows to 34% in response to climate policy.

Results for the same time period and scenario in TIAM-ECN show a significant increase in the penetration of wind energy, reaching 32% of primary energy, from 1% in the baseline scenario as shown in panel

[6] GCAM reports an implicit carbon price of $114/t$CO_2e$ in 2050 for the 50% abatement (GHG) scenario. This price is lower than the $162/t$CO_2e$ on the high carbon price scenario.

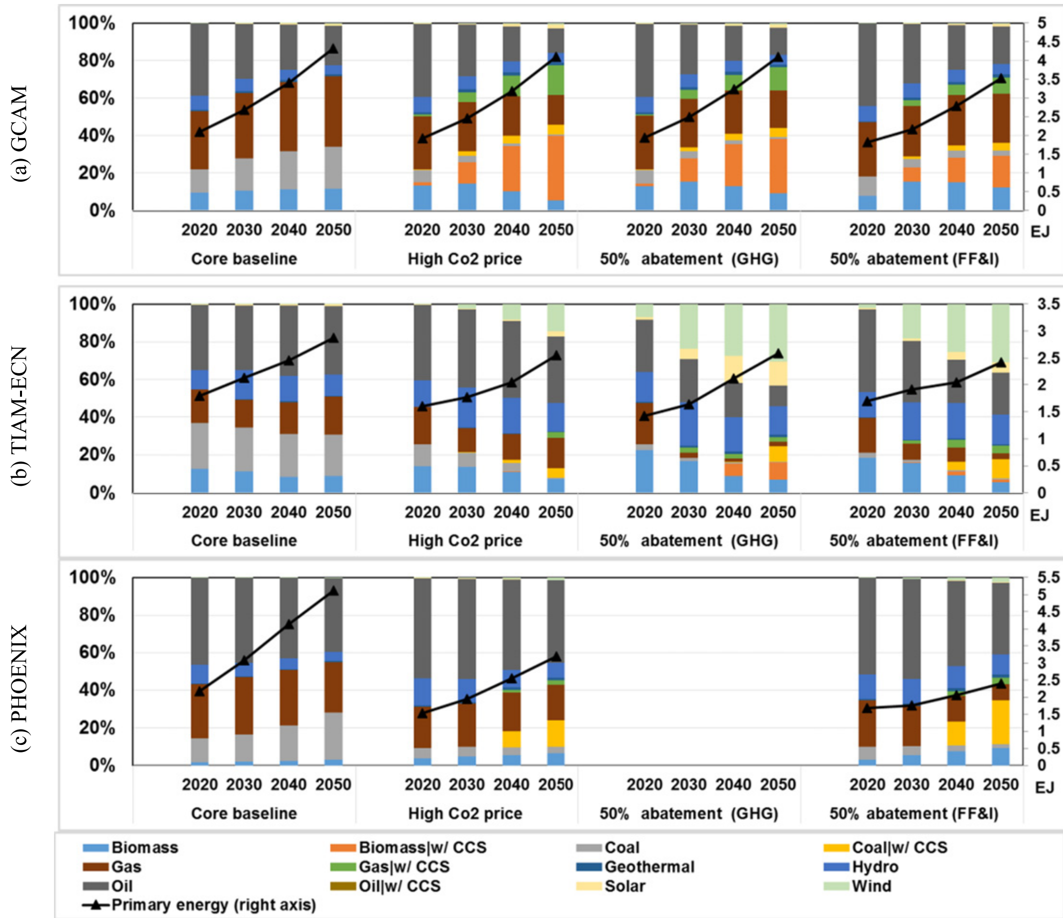

Fig. 6. Primary energy composition (left scale) and consumption (right scale).

(b). Finally, results from the Phoenix model, shown in panel (c) demonstrate that coal with CCS is deployed under the 50% abatement of CO_2 from the FF&I scenario and reaches a share of 26% of primary energy in 2050.

The evolution of the energy mix reflects some technological change, but all three models tell very different stories. While one model relies more heavily on biomass with CCS (GCAM), another model uses more coal with CCS (Phoenix, in which biomass CCS is not modeled). Both alternatives are feasible given Colombia's current state of resources and opportunities, i.e., the country is an important coal exporter and has land and water resources to produce biomass and capture CO_2. The occurrence of one or the other path will depend on different factors including the relative fuel prices of coal and biomass, the price evolution of energy substitutes such as shale gas, the costs of other low-carbon energy technologies, and local land use and environmental policies. The future demand for coal by key export markets such as China and India will influence future coal prices.

Another key conclusion, which is reflected in two out of three models, is that climate policy may increase total electricity production. This suggests that emission reductions through the electrification of the energy supply would take advantage of the potentials for hydropower and other cleaner sources. This conclusion can be seen in both GCAM and TIAM-ECN in Fig. 7, which shows the composition of electricity production and deviation in total generation with respect to the baseline. TIAM-ECN shows higher electricity generation in all policy scenarios. Although GCAM has higher generation for the carbon tax and 50% GHG policy, achieving a 50% CO_2 reduction in the FF&I scenario lowers demand by roughly 10%–20%. Finally, all models project a decrease in final energy consumed by end-use sectors (see Fig. 8). The decrease in final energy consumption may be interpreted as the adoption of energy-saving technologies and a price-induced reduction in energy consumption.

Recognizing that the models present different pathways to achieve emission reductions in response to climate policies, we describe the most relevant results from each model to provide insights on the potential abatement and technology diffusion implications of each pathway.

TIAM-ECN: Results from the TIAM-ECN model reflect a rapid decarbonization of some sectors and the deployment of cleaner technologies, mainly wind. Under the \$50/tCO_2 tax scenario, the results show a full decarbonization of the electricity sector by 2050 with higher hydropower generation and a 45% higher deployment of wind energy than in the baseline scenario, as shown in panel (b) of Fig. 7. The industrial sector cuts CO_2 emissions by 15% in 2050, as its total energy demand falls as shown in panel (b) of Fig. 9. This reduction in the industrial sector is mainly driven by a shift from coal to natural gas and improvements in energy efficiency. In addition, emissions from upstream fossil fuel production are lower than the baseline by 45%.

In the 50% abatement target on GHG scenario, the TIAM-ECN results suggest that Colombia could become CO_2 neutral by 2050, or even negative, with the adoption of biomass CCS, which captures emissions of CO_2 from biomass electricity generation. About two-thirds of the CO_2 captured in 2050 is processed in biomass-based conversion technologies, mainly for the production of synthetic fuels and hydrogen. These fuels are then used in the transportation sector, contributing to the decarbonization of the transport sector and additional improvements in energy efficiency. By reducing CO_2 emissions drastically, or even achieving net negative CO_2 emissions, sectors with lower mitigation potential bear less of the abatement burden. Electricity plays an

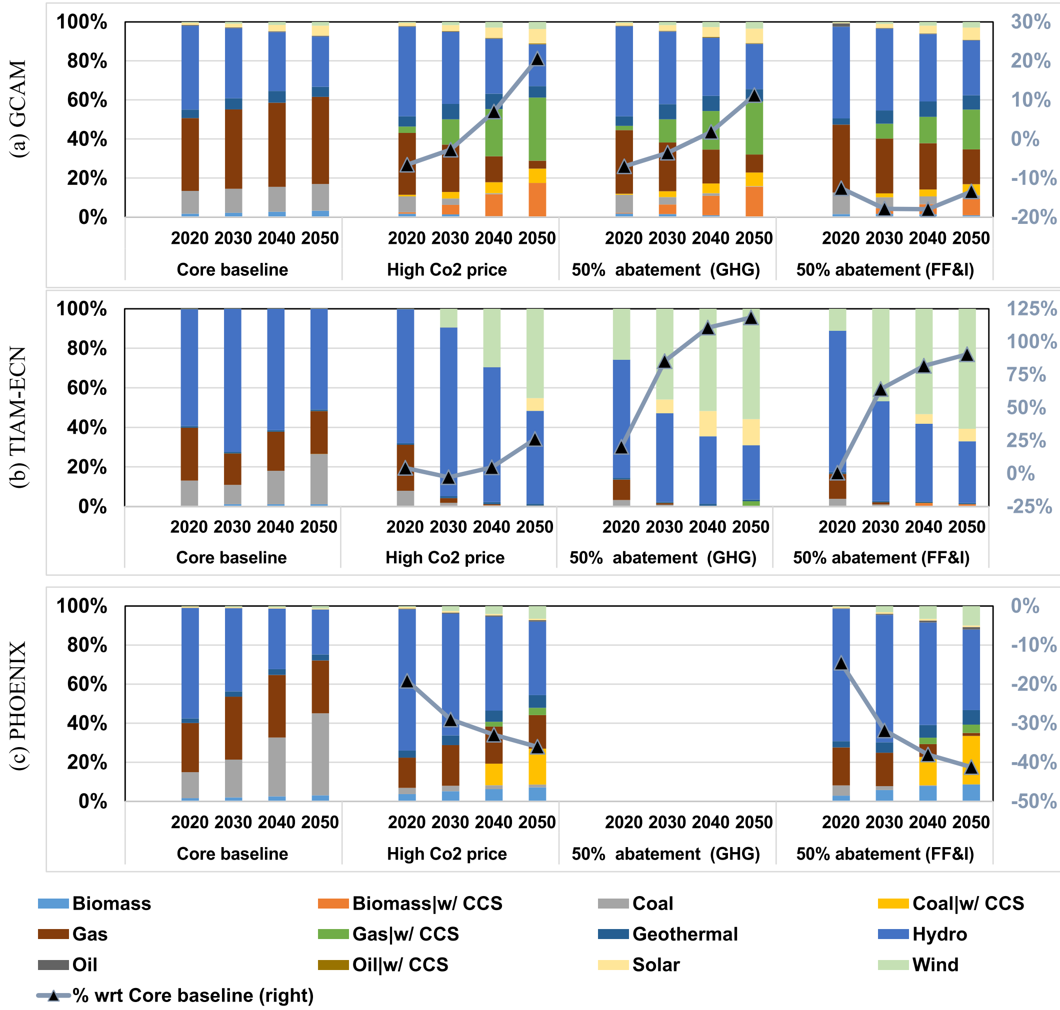

Fig. 7. Electricity production composition (left scale) and percentage change with respect to baseline (right scale, note different magnitudes).

important role in decarbonizing the energy demand sectors. Compared to the baseline, 118% more electricity is consumed (panel (b) Fig. 7), with most increases taking place in the industrial and transportation sectors.

Under the 50% abatement of FF&I CO_2 emission scenario, the electricity sector becomes CO_2 neutral as well, even though the carbon permit price in 2050 is about half of what it is in the all-GHG abatement target scenario. The reason for this is the availability of low-cost mitigation options in the electricity sector compared to other energy sectors. For Colombia this mainly refers to the deployment of hydro, wind and some solar electricity generation as shown at the far right of panel (b) in Fig. 7. The deployment of low-cost GHG mitigation options in the electricity sector relieves the pressure for other sectors to mitigate GHG, although important reductions are achieved by the industrial, transportation, commercial, residential and agricultural sectors as well.

GCAM: In the policy cases, results from the GCAM model show rapid decarbonization of the economy through the deployment of biomass and natural gas CCS (panel (a) of Fig. 7). The model predicts a lower penetration of wind and solar, due to a combination of resource availability and integration costs that result in higher generation costs than CCS technologies. With a \$50/tCO_2 tax, GCAM predicts a decarbonization of the electricity sector by 2040. Additionally, as shown in panel (a) of Fig. 9, the increased use of electricity by the end-use sectors (i.e., 21% more electricity is generated in 2050 in the tax scenario compared to the baseline) results in declining CO_2 emissions in other sectors as well. For example, the residential and commercial sector reduces emissions by 54% in 2050 due to a shift to electricity. Additionally, the use of biofuels results in a reduction in the dependence of oil and a decline in transportation emissions (12% below baseline emissions in 2050). With a 50% constraint on GHG, GCAM exhibits similar behavior to the tax scenario, as both scenarios result in roughly comparable carbon prices.

When imposing a constraint on FF&I CO_2 emissions only, GCAM predicts lower carbon prices than in the GHG emission constraint scenario because the model finds energy system CO_2 reductions to be cheaper than non-CO_2 reductions (as discussed previously). The lower carbon price leads to less pronounced shifts to low-carbon technologies than under the CO_2 price and GHG target scenarios. However, the qualitative dynamics are the same as in the other two scenarios; namely, the model decarbonizes electricity through the increased use of biomass and gas with CCS and end-use sectors shift to greater electricity use to reduce their carbon footprint.

Phoenix: Abatement of CO_2 in Phoenix is achieved through the adoption of new technologies such as CCS, some substitution toward non-energy inputs, and a reduction in economic activity. Differences between scenarios are mainly in magnitude. Final energy decreases dramatically under both policies, with the transport sector being the most affected as seen in the far right of panel (c) in Fig. 9. Within all sectors there is a shift in final energy demand toward electricity and away from fossil-based fuels, particularly coal. In the transportation sector

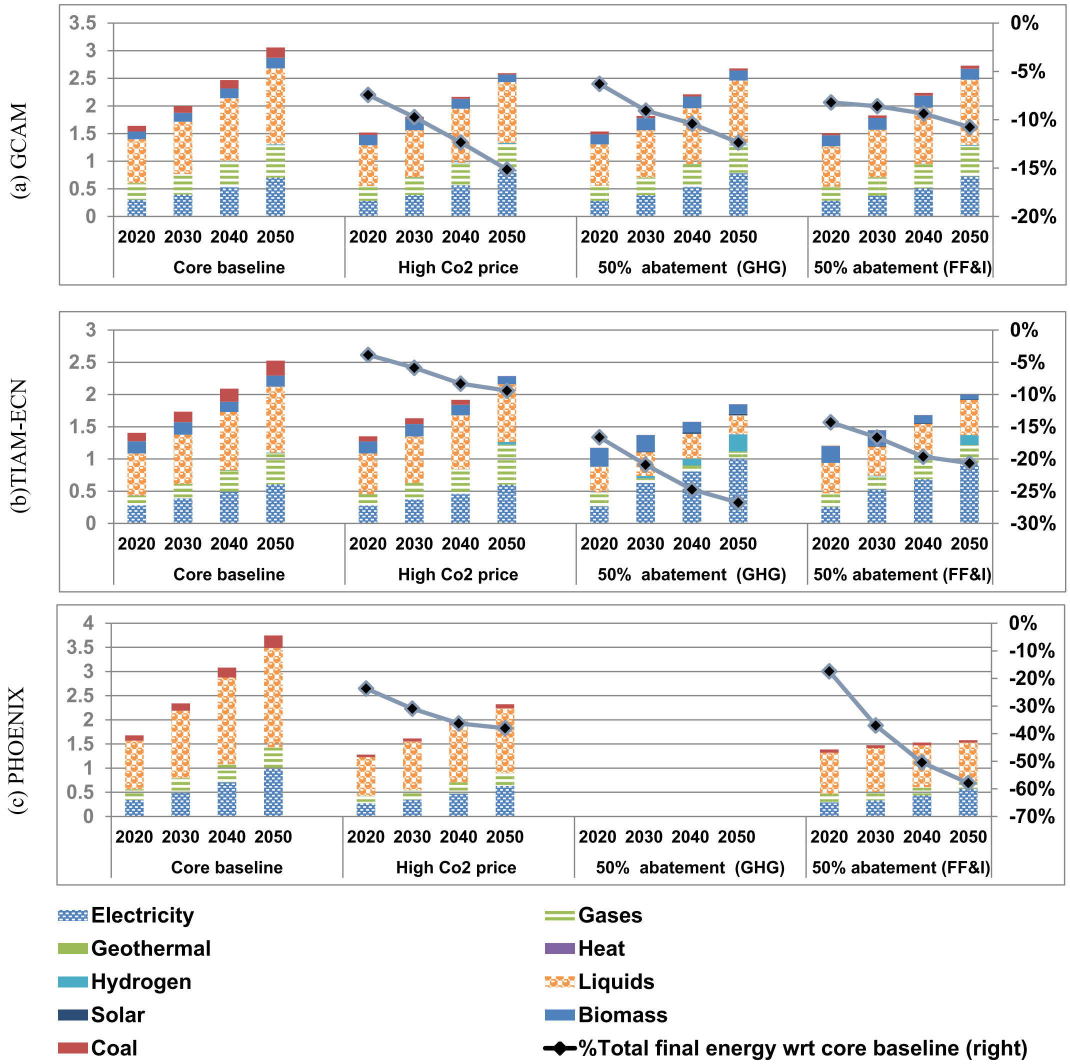

Fig. 8. Final energy composition (left scale) and percentage change with respect to baseline (right scale).

there is a concurrent increase in the demand for biofuels. Contrary to other model results, total electricity production decreases, although it does becomes a larger share of final energy relative to the baseline scenario (Fig. 7, panel (c)). The electricity that is generated becomes significantly less carbon intensive through higher participation from biomass, hydro and other renewables and through the deployment of CCS technology with coal and natural gas electricity generation.

In this section we explored the potential effects of climate policies in Colombia on CO_2 emissions and the energy system. One of the main conclusions reached is that significant CO_2 reductions can be achieved through either taxes or emission targets. All models agreed that both taxes and targets induce greater use of low carbon energy as a share of total primary energy and a reduction in sectorial final energy consumption. Finally, two out of three models suggest a shift away from fossil fuel use to electricity as a feasible mitigation option for Colombia.

Although there is much agreement across models, the greatest disagreement between these models is the relative ranking of scenarios in terms of which achieves the greatest level of abatement, and the most likely pathway to achieve these reductions. In these climate policy scenarios, the TIAM-ECN model results show that Colombia has the potential to become CO_2 neutral or even negative through the decarbonization of electric power through the greater use of hydropower, wind and biomass with CCS. In GCAM, emission reductions are achieved mainly through the use of biomass with CCS in secondary energy and the shifting of sectoral energy demand toward less carbon intensive sources like electricity. Finally, Phoenix achieves most of its reductions through the deployment of CCS in coal- and gas-fired electricity production and the shift toward greater use of electricity by sectors to meet their energy demands.

5. Climate policy costs

Achieving reductions in GHG emissions through the use of economic instruments in Colombia may lead to changes in the energy mix, improvements in energy efficiency, and the deployment of new technologies. Abatement is also achieved through reductions in final energy consumption and lower economic activity in the energy intensive sectors such as the industrial and transportation sectors. These mitigation activities may impose economic costs depending on the capacity of the country to adjust. Note that this section does not consider the potential benefits of reducing the impacts of climate change through emission mitigation nor the potential co-benefits of changes to the energy system (e.g., benefits to human health from cleaner air).

Measuring climate policy costs by examining losses in consumption and GDP is best captured by CGE models like MEG4C and Phoenix. In these models, carbon taxes are reflected primarily in the price of carbon-emitting energy sources, which reverberates through the other sectors of the economy that use energy. Although higher energy prices

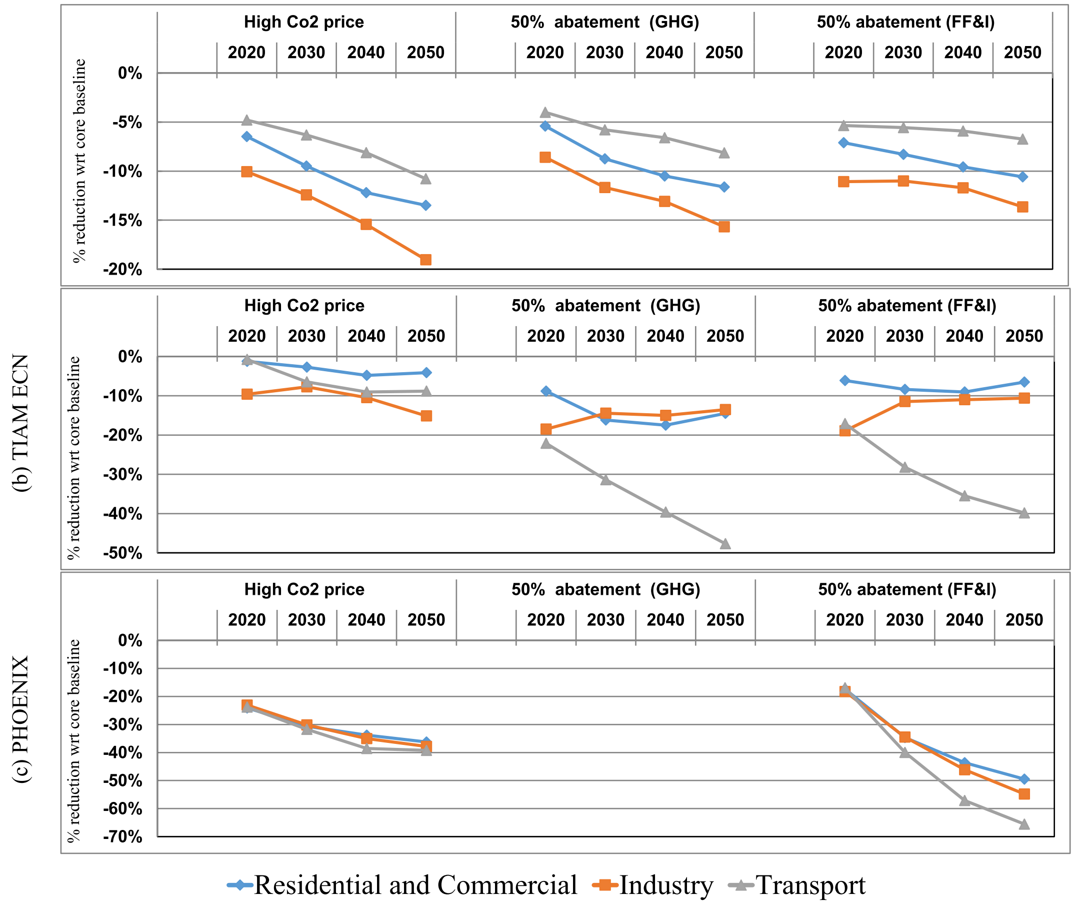

Fig. 9. Percentage change in final energy demand by sector with respect to baseline (note differences in scale).

will induce some level of substitution away from energy, it is impossible to substitute completely, which leads to higher overall prices of goods and reductions in total consumption and GDP. Fig. 10 shows the policy costs of implementing a \$50/tCO_2 carbon tax in MEG4C and Phoenix. GDP losses with respect to the baseline scenario by 2050 reach between 2.3% and 3.4%, as shown in panel (a) of Fig. **10**, while projected consumption losses are between 2.2% and 4.7% as seen in panel (b).

Both models predict GDP losses with the implementation of a carbon tax. However, in Phoenix, the fall in GDP and consumption stabilizes between 2030 and 2040, and is then resumed in 2050. This change in the trend of GDP and consumption losses occurs because of restrictions on the global adoption of CCS technology. The model assumes CCS is first used in 2025 by only a handful of countries—e.g. US, Canada, China, Australia and EU countries—followed by the rest of the world beginning in 2035. The global expansion of CCS increases the demand for coal exports from Colombia which incentivizes production and enhances GDP, but not consumption.

It is important to emphasize that the economic cost of a tax policy is heavily dependent on what is done with the revenue collected from the tax. MEG4C and Phoenix recycle carbon tax revenue back into the

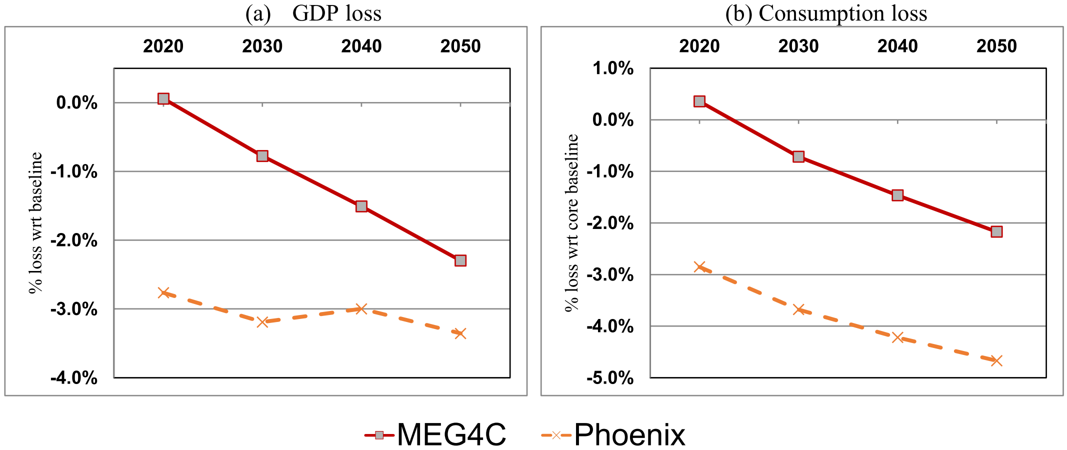

Fig. 10. Policy cost of US\$ 50 CO_2 price.

economy in the form of direct transfers to the representative consumer. Results presented in Fig. 9 show that recycling revenue in this way does not return the economy back to its baseline levels.[7] However, it is possible to dampen the effects of a carbon tax on the economy by using the revenue to lower another tax in the system (Goulder, 1995). For example, using the carbon tax revenue to reduce labor taxes may produce lower economic costs. The Models that are able to explore alternative revenue recycling strategies like these can provide key insights for the implementation of climate policy in the country.

6. The effect of model differences in model results

Variation across model results is partially explained by uncertainty over the prevailing mitigation pathways. It is also explained by differences in model base years, sources of information and unique characteristics of the models. In terms of model characteristics, Clarke et al. (2007) identify three key characteristics that can explain differences in model results: equilibrium structure, role of future expectations, and goods and services traded. The first two characteristics are particularly relevant to this analysis. Phoenix and MEG4C are general equilibrium models while GCAM and TIAM-ECN are partial equilibrium models. The fact that GDP is endogenous in CGE models and exogenous in partial equilibrium models imply that economy-wide impacts of carbon taxes and emission targets are not captured in partial equilibrium models. For this reason, we only present policy costs from Phoenix and ME4C in our analysis.

Regarding the role of expectations, TIAM-ECN assumes intertemporal optimization decisions whereas GCAM, Phoenix and MEG4C are recursive-dynamic, meaning that agents only respond to conditions in the current modeling period. One of the main implications of this difference is the selection of mitigation options. In the case of TIAM-ECN, these choices are made based on an intertemporal cost-minimizing objective, whereas in the dynamic recursive models, these choices are made based on current period cost and price information of available technologies (Clarke et al., 2007).

7. Conclusions and discussion

Currently, Colombia comprises a small share of Latin America's GHG emissions, mainly due to low levels of energy consumption and a high share of clean electricity production. However, such a low carbon economy may not be sustainable in the future. The country shows strong macroeconomic growth and stability, and it is expected that higher income will increase the demand for fossil fuels. The potential increase in carbon intensity in Colombia requires special attention for climate policy.

In this paper, we assessed the effect of carbon taxes and abatement targets on CO_2 emissions in Colombia. We performed such evaluation with four models from the CLIMACAP-LAMP project. We first compared the models' different CO_2 emission pathways and energy system developments for Colombia in a baseline scenario without climate policy. Then we compared baseline results with results from the implementation of carbon taxes and abatement targets. Despite differences across models that result in unique baseline and mitigation pathways, the models are in general agreement in terms of Colombia's sectoral abatement potential under a climate policy.

We found some consistent outcomes across the four models. In each of the models, electricity generation technologies in the baseline scenario were found to influence the carbon intensity of energy in Colombia over time. Results from the carbon tax and emission target scenarios illustrate the potential for significant CO_2 reductions. The economic efficiency of economy-wide policies supports the consideration of these policies for Colombia's low carbon development policy currently under construction. Lastly, the results show that the climate policies evaluated in this paper had the effect of allowing cleaner energy sources to enter the market, and also reduced final energy demand by end-use sectors through energy efficiency improvements and lower production.

This analysis emphasizes the important role of electricity in achieving CO_2 emission reductions. Reductions could be achieved, for instance, through increased deployment of wind and hydro as highlighted by the TIAM-ECN model; the deployment of biomass with CCS as shown in the GCAM results; or the use of coal and gas with CCS in electricity generation as shown in the Phoenix results. These alternative pathways are feasible in the country, given the state of resources and opportunities. Which pathway actually transpires, however, is dependent on the scope and characteristics of local and international climate policy and continued technological advancements in clean energy.

Our analysis shows that carbon taxes are likely to have significant economy-wide impacts as the models show that GDP in the tax scenario could be lower than in the baseline scenario by 2% to 3%. Therefore, the design of a comprehensive climate policy that includes taxes, targets or other policy instruments should include an evaluation of the costs and benefits of these instruments. Opportunities to lessen the economic impacts by, for example lowering other taxes, should be explored in conjunction with such an evaluation.

Despite the uncertainty regarding the mitigation pathway that will be imposed by a future climate policy, there are existing barriers that need to be addressed in order for any policy to be effective.

Legal barriers to non-conventional renewable energy sources need to be removed to assure their diffusion, and social and environmental conflicts should be addressed to reduce the cost of large scale expansion of hydropower. In all cases, further analysis of the implications of carbon taxes and targets in Colombia requires a broader assessment of the legal, institutional, social and environmental barriers.

Acknowledgments

The research that allowed the publication of this paper has been produced with the financial assistance of the European Union (Grant EuropeAid/131944/C/SER/Multi) in the context of the CLIMACAP project 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 the feedback and efforts from all CLIMACAP and LAMP project partners for enabling the research results reported in this article.

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