Modelling the socio-economic implications of mitigation actions in Colombia

Ricardo Delgado, Camilo Álvarez, Camilo Matajira, Ángela Cadena, Silvia Calderón.

Working paper for the CDKN project on Linking sectoral and economy-wide models
Modelling the socio-economic implications of mitigation actions in Colombia.

Ricardo Delgado¹, Camilo Álvarez², Camilo Matajira³, Ángela Cadena⁴, Silvia Calderón².

Abstract

Climate change requires worldwide efforts in order to reach greenhouse gases abatement. Despite the fact that some developing countries are not considerable emitters, some of these countries are implementing measures to deviate its emission patterns. In this paper, a methodological approach to assess the socio-economic implications of some of these potential measures is proposed and implemented to evaluate the Colombian case. The most frequent way used to assess these implications have been the use of either sectoral models or General Equilibrium Models. The methodology proposed consists on the linkage of these two kinds of models in order to assess the impacts in both the sectoral activities and the economic wide parameters. This paper focuses on measures on the energy sector and the impacts in the economic growth of the country. The main finding is that a carbon tax does not affect significantly the macroeconomic indicators and yet reached important abatements, especially if low oil prices are considered as baseline.

1 Introduction

In 2004, Colombia emitted 180 million tons of CO₂eq, which represents the 0.04% of the world’s emissions during the same year (IDEAM, 2009). Despite the small share in the world’s total emissions, the country has made some efforts in order to identify and to implement CO₂ mitigation actions. Those efforts have been made by both, private and public sectors supported by universities and research centers. On one hand, there are private initiatives devoted to reach clean development paths for the country as can be seen in Delgado et al. (2014) and Cadena et al. (2009). On the other hand, the public sector has invested important resources and policy actions in order to build a National System for Climate Change (SNCC). This system is composed of: the Executive Commission for Climate Change (COMECC); a Financial Management Committee; an Orientating Group; a Consulting Group and, four Permanent Sub-Commissions. The SNCC is intended to enhance mainly four strategies aimed to transform the way the country understands climate change and sustainable development in general. These four strategies are: the National Adaptation Plan; the Low Carbon Development Strategy (CLCDS); the National Strategy for Emissions Reduction due to Deforestation and Forest Degradation; and, the Strategy for Financial Protection against Disasters. In all this experiences, the academic sector has supported both public and private sectors in their initiatives. Currently, the country is carrying out two relevant studies. The first one is under the

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direction of MADS and pursues the identification of clean development paths for the country, and is part of the CLCDS and of the MAPS-Colombia work; the second one aims to identify potential impacts of the climate change in Colombian economy. To the date, studies have been assessed from the point of view of the CO2 mitigation potential and sectoral costs derived from the mitigation actions. This study aims to join both approaches by assessing the economic impacts of mitigation actions, performed in the energy sector, across the whole economy. By doing so, we expect to provide policy makers with valuable information about the "associated impacts" of implementing mitigation actions in certain sectors.

As previously, Colombia is not a relevant GHG emitter in the global context. Additionally its emission matrix differs from most of the countries. During 2004, 56.6% of the world’s emissions were due to the use of fossil fuels; in Colombia, in contrast, only 36.65% of the national GHG emissions were associated with this sector in the same year. Furthermore, the most important GHG emitter in the country is the agricultural sector, which represented 38% of the GHG emissions in 2004. This fact is explained by the high renewable share in the Colombian power sector and by the importance of the agricultural sector in the Colombian economy. The Colombian electricity emissions are low due to the high hydro share in the power matrix. In the last years, renewable sources have provided up to 80% of the whole electricity requirements. The “clean” Colombian energy mix might change due to the increase on the demand and to the need to incorporate firm energy to complement the renewable share on the power generation. For these reasons, despite of the fact that Colombian energy sector is not the biggest emitter; it is interesting to understand the relationship between the economy and mitigation actions in this sector.

The proposed methodology includes the use of a bottom up (BU) model for sectoral analysis and a top down (TD) model for macroeconomic impact evaluation. For the energy sector, MARKAL-Colombia model was used. This model was built and is maintained by the Universidad de los Andes and will be further explained in this document. On the other hand, for the macroeconomic impact evaluation, a Computable General Equilibrium Model (CGE) is used. This model is the MEG4C. It was built, used and maintained by the National Planning Department of Colombia (DNP). This document summarizes the results obtained up to the date by linking both models to evaluate the impacts of measures such as: carbon taxes, equivalent carbon caps, a renewable generation portfolio and a fossil fuels substitution in the industrial sector program.

In previous studies performed by the authors, Colombian MARKAL has shown that a carbon tax on Colombia will change the share of fossil fuel consumption. Additionally, MEG4C concluded that a carbon tax in Colombia would lower GDP and employment. Both MARKAL and MEG4C are useful for the purpose they were built for; they have strengths and weaknesses, but working with each model separately may give us biased results.

MARKAL and other bottom-up models (e.g. LEAP, MESSAGE) provide a detailed description of the sector they represent and are very useful for assessing technological change and policy analysis in their own sector. Nevertheless, bottom-up models give answers to a specific sector of the economy, ignoring the side effects that the modeled sector can have on households,
firms and the economy as a whole. For example, MARKAL works based on a macroeconomic scenario of energy demand by industry, commerce and households, if we measure the impact of a carbon tax, the energy supply share of fossil fuels will decrease and the price of energy will rise. But, if energy prices go up, enterprises will be less competitive; imports will rise, national production will fall and unemployment will rise too. As a consequence, energy demand will decline and the macroeconomic scenario, in which MARKAL was built on, will change and so the previous results with MARKAL will not hold, or will not be optimal. In conclusion, MARKAL and the other BU models could lead into biased results, the same problem also happens with the TD models.

On the other hand, the MEG4C and the other models represent the whole economy and the interaction between the different sectors. These kinds of models are used for many purposes including macroeconomic forecasting, monetary and fiscal policy, international trade and climate change etc. But MEG4C had some shortcomings concerning our analysis: first, the production function in the energy sector is a CES (constant elasticity of substitution) so the share of the energy sector and the energy supply is exogenous. This means that, under a carbon tax, fossil fuels will always have the same participation in the energy mix when it will be expected a decline in its participation. This would bias the results because enterprises might switch to a less pollutant and cheaper sector, as a consequence the MEG4C over estimates the effects of a carbon tax. Even if we make some adjustments to the MEG4C, it will always be better to use a tool as MARKAL.

Taking into account both strengths and limitations of TD and BU models, we chose to link both models in order to evaluate mitigation policies. The results show that the impacts on the macroeconomic indicators are small positive and negative depending on the evaluated measure and the abatement implies penetration of renewable in the power mix and electricity in the transportation.

The remainder of the paper proceeds as follows. In section 2, a brief summary of the literature concerning the linking of this type of models is presented. In section 3, the models used for the evaluations are shown and described. In section 4, the methodological approach is presented. Section 5 is devoted to the results and analysis. Finally, the section 6 concludes and suggests further work.

2 Literature review
As a starting point for this task, a brief literature review was performed. Following Uribe (2012), there are four types of methodologies for linking Top-Down (TD) and Bottom-Up (BU) models: (1) methodologies in which there are two way links or connections between TD and BU; (2) methodologies in which the TD are enriched by some elements of the BU; (3) models in which the BU are enriched using the TD and (4) models in which TD and BU are completely integrated and solved in the same optimization process.

Two way links between TD and BU
This approach joins TD and BU models by sharing information and running sequentially one after the other. For instance, TD exports macroeconomic forecasts and energy demands, the
BU use this information and exports energy prices, elasticities and participation of the different energy sectors in the economy, then the TD takes this inputs and updates its forecasts and so on until convergence.

**BU extending TD**
The second category of models uses BU model results to calibrate some parameters of the TD. In particular, the BU results are frequently used to calibrate the production function of the energy sectors in the TD model. For example, Schafer and Jacoby (2005) enrich a CGE model with two specific models, one to determine the types of transport used by households (private or public transport) and MARKAL to determine the technological characteristics of the transportation sector. The first model is used to calculate the share parameter of household demand for transport function, while the second gives the substitution elasticity between energy goods and other inputs. However, once the model is calibrated Schafer and Jacoby (2005) make a one way link from their CGE to MARKAL. In this sense, this model is not completely a BU extending a TD, but once calibrated it could also be seen as a TD extending a BU.

**TD extending BU**
The third category is when the TD extends the BU model. This is the case when BU models, like MARKAL, receive their inputs from a CGE, a growth accounting model or an econometric model. This kind of models can even have a two way connection between a TD and a BU, but there main interest is still the results from the BU model. MARKAL-MACRO (Hamilton, Goldstein, Lee, & Morris, 1992) is an example of the latter, in this model the MACRO model is used for macroeconomic forecasting; but its main objective is to quantify the change in energy demand due to price change in energy. In this sense, the focus in MARKAL-MACRO is not the macroeconomic impacts of a mitigation policy but to extend MARKAL allowing energy demand to change.

**TD and BU in the same optimization model**
The last category is made up from models in which both the TD and the BU models are merged in the same optimization program. Bohringer and Rutherford (2005) propose one of these models but they have not conducted empirical exercises yet.

### 3 Modelling tools
To reach the paper goal –to assess relevant mitigation actions and its expected impacts in the whole Colombian economy– we use a set of modelling tools that may enable us to evaluate these measures. The energy sector is one of the most relevant GHG emitter in the Colombian economy. By this reason, a sectoral bottom up model was used to find out the impacts of carbon tax and mitigation actions in its activities. On the other hand, a top down modelling approach was used to assess the macroeconomic impacts of such kind of measures. These models will be further explained will be presented in next three subsections.

#### 3.1 Sectoral model **MARKAL**

##### 3.1.1 Model description
MARKAL (Fishbone L.G., Abilock H., 1981) is an integrated multi-period linear programming model designed to assess national and regional energy systems. It evaluates the optimal contribution of different mixes of energy carriers and technologies to fulfill an objective of a given country or region. The model has been continuously evolving, most recently enhanced to allow for the evaluation of national and multinational GHG emissions control strategies.

MARKAL was developed in the Energy Technology System Analysis Programme -ETSAP-, a co-operative project of national experts under the aegis of the International Energy Agency –IEA-. The MARKAL family models are being used in more than twenty developed countries since more than two decades and in a few developing countries like India, China, Turkey, Vietnam, Colombia, Mexico and Brazil.

In order to perform these analysis MARKAL requires input data like availability of indigenous primary energy, imports and exports of energy carriers and its corresponding prices, forecasts of useful energy demand for each time period, and a technical and economic description of the existing and new technologies.

The development of a MARKAL model is based on network representation of the energy flows through different groups of production and demand technologies that is called the Reference Energy System –RES-. In the RES one draws the energy flows from the sources to the end-use through the technologies that are used to extract, transform distribute energy carriers and provide energy services.

### 3.1.2 Colombian model description

And extended and updated version of the MARKAL-Colombia model (Cadena A. and Haurie A., 2001) was used for mechanism implementation evaluation. This model has been use to analyse different energy policies in Colombia (Cadena A., Moreno J.B., 2004) as well as to identify joint projects to curb CO₂ emissions between Colombia and Switzerland (Cadena A. et al., 1999).

Several additional generation technologies were included to cover all possibilities of the use of renewable sources. The update was required since the last available version was tuned with 1990 data. Base year was tuned with data from the UPME and Hydrocarbon National Agency (ANH by its Spanish acronym) energy balances. The planning horizon goes from 2005 to 2045.

From the supply side both heavy and light crude production was considered, as well as thermal and metallurgical coal, natural gas (in total there 35 supply side technologies were modeled). Exports included light crude, thermal and metallurgical coal, fuel oil, diesel oil, gasoline, jet fuel, and electricity. From the demand side seven sectors were modeled: residential, industrial, commercial, public, transportation, building, agriculture and non-energy uses. Each sector comprised different end uses with its corresponding technologies (66 end use demands and 112 demand devices were modeled). Transformation processes were also modeled such as existing power generation technologies (thermal coal and gas plants, fuel oil plants, gas turbine plants, diesel and hydro plants). Expansion possibilities were considered as generic plants. Another transformation processes were modeled, such as the Barranca and Cartagena refineries, industrial heat and steam production, coke, briquettes and other minor...
transformations (15 process technologies and 23 conversion technologies were modeled). Finally, the requirements of firm energy for the Colombian power system were modeled as an upper limit in the hydraulic generation, set as 70% of the total generation in the period.

3.2 Economy wide model

3.2.1 Model description

Macroeconomic model M was inspired in two models: MARKAL-MACRO (Loulou, Goldstein, & Noble, 2004) and Chkravarty (1962). The structure of the model is the following:

\[
\begin{align*}
\max \quad & U_0 \left\{ C_t \right\} \\
\text{subject to:} \\
Y_t &= A_t K_t^\beta L_t^{1-\beta} \\
K_{t+1} &= Y_t - C_t - EC_t + (1-\delta)K_t
\end{align*}
\]

Where \( C_t \) stands for consumption in period \( t \); \( Y_t \), total production of the economy; \( A_t \), total factor productivity; \( K_t \), stock of productive capital; \( L_t \), labor force; \( EC_t \), total energy costs; \( \rho \) and \( \eta \), preference parameters over consumption; \( \delta \), depreciation parameter and \( \beta \), capital share in the production function. \( C_t, K_t \) and \( Y_t \) are endogenous to the model; in contrast, \( A_t, L_t, EC_t \) and the other parameters are exogenous.

Model M is used, primarily, for GDP growth projections and to model the tradeoff between total energy costs and GDP growth: higher energy costs mean less income both to consumption and investment, and less investment on productive capital translates into lower GDP growth.

3.2.2 Colombian model description

Model M was calibrated in the following way: labor force was taken from DNP’s population and labor force projections. Total productive capital in Colombia at 1980 was estimated by Hofman (1992) and Hofman (2000); annual gross capital formation was added to find a proxy for the stock of capital at 2005. Share parameters were estimated using a constrained regression. Total factor productivity was implicitly calculated to fit the production function with Colombian GDP at 2005.

3.3 Economy wide model MEG4C

3.3.1 Model description

The Computable General Equilibrium Model of Colombia for Climate Change - MEG4C acronym in Spanish - is related closely to previous models like the MEGF (Bussolo, Roland-Holst, & van der Mensbrugge, 1998) and the model (Burniaux, Nicoletti, & Oliveira-Martins, 1992). The currently MEG4C quantitative basis is the Social Accounting Matrix 2005, developed with the methodology of Corredor & Pardo (Corredor & Pardo, 2008) with 15 economic sectors. MEG4C’s production structure is described by the Figure 1.
Sectoral production is made by mixing productive factors and intermediate consumption using a Leontief production function. The productive factors considered in this model are capital, energy and labor (KEL); substitution between factors is modeled using a Constant Elasticity of Substitution (CES) function.

On the other hand, the model includes four agents: households, businesses, government, and rest of the world. Businesses and households maximise their utility while government and the rest of the world are exogenous. In this process, all markets clear (except unskilled labor market) and there is an imperfect substitution between domestic and foreign goods, i.e., a constant transformation function (CET).

The MEG4C is recursive dynamic therefore agents are "myopic" and the link between periods is given by the evolution of the capital stock.

4 Methodology

4.1 First approach

Our initial approach was a two way link between MEG4C and MARKAL. In this sense, MEG4C will provide sectoral GDP to MARKAL. Then, MARKAL will return energy shares, electricity price and investment cost for the electrical sector. The impact in macroeconomic indicators considered was that higher energy prices or restrictions would imply a change in the energy matrix, allocating scarce resources to, perhaps, cleaner energy generation but more demanding of resources. The soft link will be performed like the next figure:
We implemented this approach but had some shortcomings which we describe in detail so that future modelers can benefit from our experience. The first shortcoming was that MARKAL and MEG4C were not meant, initially, to be linked: both models were constructed by researchers in different entities, with different purposes in mind. The second shortcoming was the problem of convergence between the models.

With regards to the first shortcoming, communication between MEG4C and MARKAL was not straightforward because they have different sectoral disaggregation. First, MARKAL added all industry into a single sector: so the richness of MEG4C’s SAM could not be exploited. To fix this, we aggregated all industrial sectors in the SAM in order that MEG4C have a single industry sector too. The next problem arise after having a peer review: MARKAL considered a whole set of generation technologies but DANE’s 2 digit SAM –the foundation of the MEG4C- was too aggregated. For instance, MARKAL considers electric generation with coal, hydro, natural gas, oil derivatives while MEG4C considered all this as a single electricity sector with a fixed production function. This was a major shortcoming because the main idea of how changing energy shares affect the economy was that a mitigation action –like a carbon tax- changed the energy matrix in favor of more capital or labor intensive fuels, allocating scarce resources to more demanding energy sectors.

The other main shortcoming was the technical issue of convergence. Our strategy involved fixing energy and investment prices in the CGE. The problem was that for some values of energy prices and investment the model wasn’t able to find a feasible solution. So, although for relatively little changes in prices the model run correctly, for some iterations it didn’t. Considering we needed to run several iterations, we concluded that this approach was not reliable.
4.2 Current approach

Taking into account the limitations mentioned before, we implemented a more aggregated linking strategy. In this approach we wanted to model specifically the inverse relation of energy costs and GDP growth. For this, we added a model M that works as an extension of MEG4C.

This is a three model linking approach run in the following sequence. First, the endogenous growth model –M– provides the CGE –MEG4C– with GDP projections. Second, MEG4C produces sectoral GDP, used as energy demand drivers in MARKAL. Third, MARKAL optimizes the energy sector and provides M with new annual total energy costs. The idea behind the three model approach is that GDP growth is inversely related to the cost of energy: higher energy costs mean less money available for either consumption or investment; this translates into less investment on productive capital and lower GDP growth. In turn, lower GDP growth leads to lower energy demand, and lower energy costs, which raise GDP. Concerning the carbon tax, it is placed in MARKAL: MARKAL total energy cost will raise causing investment and GDP growth to decline in the other models. The recycling mechanism considered was direct transfer to households and this transfer was implemented in model M. The following figure shows the approach:

![Linking approach diagram]

Figure 3. Linking approach

We implemented the model, and the results are shown in the next section. We submitted this model to peer review and obtained the following comments which will be considered in future work. First, due to the macroeconomic focus we are implicitly assuming that the carbon tax impacts all economic sectors in the same manner. Peers also said that we could continue working in our first approach and gave us some advice on how to deal with the lack of information considering the 2 digit SAM. This information can also help us improving our current methodology.

Using the latest approach, we modeled three groups of mitigation actions: carbon taxes a, caps on carbon emissions other energy programs. Three taxes were evaluated: $10, $20 and $50 per CO₂ ton. The taxes were evaluated considering that they could be implemented in presence or absence of a recycle mechanism. This mechanism was modeled as a direct transfer to the households. The second mitigation action modeled was a limit on the emissions of carbon. The limit was defined to be equivalent to the emission levels reached by implementing
each tax. In other words, the limit was defined as the cumulative emissions of each tax scenario (without recycler mechanism). The third group of mitigation actions is composed of two energy programs. The first program is renewable generation portfolio. This portfolio starts in 2015 and considers the installation of cogeneration facilities, small hydro plants, geothermal plants and small (50MW) wind farms. The second energy program consists on the substitution of fossil fuels in the industrial heat and steam processes by electricity. Finally, the taxes were evaluated in two different international oil price scenarios: a low price scenario in which the oil reach and maintains a cost of $80 per barrel; and, a medium price scenario of $100 per barrel. Summarizing, we have one baseline, (without mitigation actions), and three tax scenarios for the low oil price assumption; and, a baseline, three tax scenarios and three limit on emissions scenarios for the medium oil price assumption.

5 Results and analysis

In this section we summarize the main findings of this study. This section presents first the results related to the abatements of the evaluated actions. Once presented these abatements, the involved economy wide impacts are presented too. In both cases, the results are presented for the baseline scenario wish considers a medium oil price forecast. For this scenario, a set of carbon taxes, limits on emissions and energy related programs were evaluated. Furthermore, for the carbon taxes, a direct transfer to household was considered. For the two main measures, sensitivity to the oil prices was performed, and the results are presented right after the summary of the findings for the baseline.

Regarding to the emissions it is important to highlight that the baseline of emissions do not consider those related to waste and land use. These activities are not accounted into the MEG4C and for this reason we did not incorporate them into our analysis. Table 1 shows the percentage of reduction on emissions of each mitigation action compared to the baseline in each period. It can be seen from this table, that a tax under $20 per ton does not allow abatements above 3% in any period. Furthermore, for most of the years the abatements reached by a $10 tax is close to the one reached by a $20 one. In contrast, a tax of $50 reduces emission in a higher amount and earlier in time.

Results with and without recycler mechanism are similar, with a slightly trend to reduce more emissions in absence of the recyle, especially in the last periods. In total, a $50 carbon tax can reduce Colombian energy related cumulative emissions by 33% until 2045; it is up to 10.4% of the emissions in the considered sectors. If a smaller tax is considered, the total abatement is less than 1% of the national emissions for a $10 tax and less than 1.5% for a $20 tax.

Regarding to the limit on the emissions, despite the fact that the total abatement is equivalent, the abatement path is different. In the limit on emissions, the investments and changes are postponed to the last periods. For this reason during the first periods, emissions in do not decrease or even increase. This increase is compensated with bigger abatements in the last periods. This behavior can be explained by the assumption of decreasing costs of new technologies in time. The responses of the energy sector to the evaluated measures are: increase on the penetration of electric vehicles; increase in the penetration of non
conventional renewable sources for the power generation; and, in the case of the industries, there is a small substitution of coal towards natural gas. The remaining final consumption sectors are not able to substitute fuels or to incorporate more efficient technologies since they are already included in the baseline.

Table 1. CO₂ emission deviation with respect to BAU for given mitigation actions in the medium oil price scenario

<table>
<thead>
<tr>
<th>Year</th>
<th>Carbon tax without recycling</th>
<th>Carbon tax with recycling</th>
<th>Carbon CAP equivalent</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$10</td>
<td>$20</td>
<td>$50</td>
</tr>
<tr>
<td>2010</td>
<td>-0.01%</td>
<td>-0.41%</td>
<td>-1.05%</td>
</tr>
<tr>
<td>2015</td>
<td>-0.01%</td>
<td>-0.06%</td>
<td>-3.53%</td>
</tr>
<tr>
<td>2020</td>
<td>-0.18%</td>
<td>-0.41%</td>
<td>-5.77%</td>
</tr>
<tr>
<td>2025</td>
<td>-0.31%</td>
<td>-0.60%</td>
<td>-9.09%</td>
</tr>
<tr>
<td>2030</td>
<td>-0.09%</td>
<td>-0.13%</td>
<td>-10.82%</td>
</tr>
<tr>
<td>2035</td>
<td>-0.22%</td>
<td>-0.27%</td>
<td>-15.06%</td>
</tr>
<tr>
<td>2040</td>
<td>-0.15%</td>
<td>-2.47%</td>
<td>-16.50%</td>
</tr>
</tbody>
</table>

Source: own elaboration

Additionally, two energy programs were assessed. The first one consisted on a renewable portfolio for power generation. This portfolio includes four technologies: industrial biomass cogeneration, small hydro plants, geothermal facilities and, small 50MW wind farms. The second evaluated measure in this group was the substitution of fossil fuels in the industry by electricity. The modeled substitution was devoted to fulfill a share of the heat and steam requirements. Table 2 summarizes the abatements reached by these measures. It can be seen that these programs, in terms of abatement, obtain results comparable with the carbon tax of $20 per CO₂ ton. However, the abatement keeps a growing path, while in the tax and in the cap measures the size of the abatement varies between periods. The total abatement of these measures is 0.64% and 1.56% of the emissions in the baseline until 2045 for the renewable portfolio and for the use of electricity in the industry, respectively. The fact that the abatement derived from an increase of the renewable energies in the power generation might be explained by the fact that the new facilities are going to replace some hydro plants already installed.

Table 2. CO₂ emission deviation with respect to BAU for given mitigation actions in the medium oil price scenario

<table>
<thead>
<tr>
<th>Year</th>
<th>Renewable portfolio</th>
<th>Electricity for industry</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>-0.03%</td>
<td>0.08%</td>
</tr>
<tr>
<td>2015</td>
<td>-0.20%</td>
<td>0.00%</td>
</tr>
<tr>
<td>2020</td>
<td>-0.30%</td>
<td>0.08%</td>
</tr>
<tr>
<td>2025</td>
<td>-0.42%</td>
<td>-0.31%</td>
</tr>
<tr>
<td>2030</td>
<td>-0.70%</td>
<td>-1.29%</td>
</tr>
<tr>
<td>2035</td>
<td>-1.07%</td>
<td>-2.22%</td>
</tr>
<tr>
<td>2040</td>
<td>-1.13%</td>
<td>-3.14%</td>
</tr>
</tbody>
</table>

Source: own elaboration
Table 3 presents the sensitivity performed to the oil prices. This sensitivity modifies mainly the baseline. If oil price decreases from its current values, some technological changes considered in the previous case do not happen. This is the case of electricity in the transportation sector. With a low oil price scenario, electricity is not included into the minimum cost energy mix. This is the main reason that explains the higher abatements reached for the same measures compared to the previous case, as can be seen in table 2. In other words, as the oil price increases, the baseline includes new technologies. The available technologies are, at the same time, cleaner. In this sense, an increase in the cost of fossil fuels might have similar impacts to the obtained by taxing the emissions. This result is quite intuitive since the main effect of a tax is to increase the costs to use energy. The relevant issue is that with a medium oil price scenario, the Colombian energy mix changes becoming even cleaner than it is today. This means that additional abatement measures are hard to be implemented and requires higher investments, if compared with other countries with more pollutant energy baskets.

Table 3. CO₂ emission deviation with respect to BAU for given mitigation actions in the low oil price scenario

<table>
<thead>
<tr>
<th></th>
<th>Carbon tax without recycling</th>
<th>Carbon tax with recycling</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$10</td>
<td>$20</td>
</tr>
<tr>
<td>2010</td>
<td>-1.27%</td>
<td>-1.25%</td>
</tr>
<tr>
<td>2015</td>
<td>-2.49%</td>
<td>-2.86%</td>
</tr>
<tr>
<td>2020</td>
<td>-2.25%</td>
<td>-2.45%</td>
</tr>
<tr>
<td>2025</td>
<td>-2.16%</td>
<td>-2.83%</td>
</tr>
<tr>
<td>2030</td>
<td>-1.95%</td>
<td>-2.62%</td>
</tr>
<tr>
<td>2035</td>
<td>-2.93%</td>
<td>-4.82%</td>
</tr>
<tr>
<td>2040</td>
<td>-3.10%</td>
<td>-6.91%</td>
</tr>
</tbody>
</table>

Source: own elaboration

In a low oil price scenario, a carbon tax boosts the use of electricity: 10.56%, 19.94% and 48.17% increase in electricity consumption (at 2040) in presence of a $10, $20 and $50 tax. There are no major changes in electricity consumption if a medium oil price scenario is considered (the increase in electricity consumption is due to the higher fossil fuels prices). In a low oil price scenario, a carbon tax boosts the use of natural gas: 5.81%, 11.33% and 12.54% increase in natural gas consumption (at 2040) in presence of a $10, $20 and $50 tax. There are no major changes in natural gas consumption if a medium oil price scenario is considered.

Finally, in a low oil price scenario, a carbon tax depresses the use of coal: 8.24%, 13.73% and 47.10% decrease in coal consumption (during the 40 years) in presence of a $10, $20 and $50 tax. In a medium oil price scenario, a carbon tax diminishes the use of coal: 0.74%, 8.21% and 61.61% decrease in coal consumption (during the 40 years) in presence of a $10, $20 and $50 tax. Above a 20 USD tax, renewable becomes competitive for power generation instead of the substitution between coal and natural gas.

Regarding to the macroeconomic impacts, table 3 shows GDP deviation with respect to Business as Usual (BAU) scenario for given mitigation actions; there are four main ideas concerning the results: first, imposing a carbon tax lowers GDP. In fact, in 2020 GDP decreased...
with respect to BAU \( \left( \frac{GDP_{\text{tax}}}{GDP_{\text{BAU}}} - 1 \right) \) by 0.58\% for a USD $10 carbon tax; 0.56\%, for a USD $20; 0.77\%, for $50. However, we have reasons to consider that this result is biased – it’s smaller in magnitude that it should be. One reason is that the model is only taxing the energy sector – which represent a third of total GHG emissions. The other reason is that we are ignoring the costs of enforcing the tax.

Second, implementing a recycling mechanism can reduce the GDP impact of a carbon tax in the long run. Table 3 shows that imposing a $10 carbon tax without recycling reduced GDP by -0.31\% and with transfer by -0.25\%; a $20, -0.45\% and -0.22\%; and a $50, -0.79\% and -0.36\%. This means that the potential side effect of a carbon tax can be reduced by transferring the collected money to the households. Nevertheless, carbon tax with transfer still has a negative effect on GDP, this means “there is no free lunch” in mitigation actions.

Third, GDP reduction due to carbon cap result very similar to carbon tax with transfer to the households. In fact, except for carbon cap 10$ scenario the others differ very little with they counterparts. Yet, our analysis ignores the mechanism of how GHG emissions are allocated. This is, in our model MARKAL works like a central planner allocating resources to minimise cost, but in real life we ignore how emissions will be distributed among people and firms. This, in turn, can raise energy costs, so cost may be underestimated.

Fourth, both the Renewable Portfolio and the Electricity for Industry scenarios had the same negative impact on the economy. Difference in energy costs where very small between both scenarios, so the GDP projection was practically the same – in other words, the difference between GDP growth in both was below our convergence criterion. Table 3 shows that imposing this scenarios led to a reduction in GDP with respect to BAU. This reduction is, in magnitude, very similar to the impact of a $10 carbon tax without recycling, to a $20 carbon tax with recycling and to a $20 carbon cap equivalent.

<table>
<thead>
<tr>
<th></th>
<th>Carbon tax without recycling</th>
<th>Carbon tax with recycling</th>
<th>Carbon CAP equivalent</th>
<th>Renewable portfolio &amp; Electricity for industry</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$10</td>
<td>$20</td>
<td>$50</td>
<td>$10</td>
</tr>
<tr>
<td>2010</td>
<td>-0.28%</td>
<td>-0.18%</td>
<td>0.07%</td>
<td>-0.37%</td>
</tr>
<tr>
<td>2015</td>
<td>-0.64%</td>
<td>-0.58%</td>
<td>-0.55%</td>
<td>-0.68%</td>
</tr>
<tr>
<td>2020</td>
<td>-0.58%</td>
<td>-0.56%</td>
<td>-0.77%</td>
<td>-0.55%</td>
</tr>
<tr>
<td>2025</td>
<td>-0.42%</td>
<td>-0.47%</td>
<td>-0.78%</td>
<td>-0.37%</td>
</tr>
<tr>
<td>2030</td>
<td>-0.31%</td>
<td>-0.44%</td>
<td>-0.76%</td>
<td>-0.29%</td>
</tr>
<tr>
<td>2035</td>
<td>-0.28%</td>
<td>-0.41%</td>
<td>-0.74%</td>
<td>-0.25%</td>
</tr>
<tr>
<td>2040</td>
<td>0.08%</td>
<td>-0.01%</td>
<td>-0.28%</td>
<td>0.14%</td>
</tr>
</tbody>
</table>

Source: own elaboration
Results for wages are presented in table 4. Results show that for 2020 and afterwards, wages – with respect to BAU – decrease in every given scenario. This means that wages follow GDP’s negative trend but impact is lower in magnitude. In other words, reduction in growth is distributed not only among wages but also in the other productive factor in the economy – like capital. Also the negative impact in wages would start after 2020. Finally, the higher the tax – or the cap- the more time the economy will need to interiorize the negative effects of the measure.

Table 4. Wage deviation with respect to BAU for given mitigation actions

<table>
<thead>
<tr>
<th></th>
<th>Carbon tax without recycling</th>
<th>Carbon tax with recycling</th>
<th>Carbon cap</th>
<th>Renewable portfolio &amp; Electricity for industry</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$10</td>
<td>$20</td>
<td>$50</td>
<td>$10</td>
</tr>
<tr>
<td>2010</td>
<td>0.00%</td>
<td>0.01%</td>
<td>0.02%</td>
<td>0.00%</td>
</tr>
<tr>
<td>2015</td>
<td>0.08%</td>
<td>0.09%</td>
<td>0.17%</td>
<td>0.05%</td>
</tr>
<tr>
<td>2020</td>
<td>-0.12%</td>
<td>-0.09%</td>
<td>0.02%</td>
<td>-0.16%</td>
</tr>
<tr>
<td>2025</td>
<td>-0.21%</td>
<td>-0.17%</td>
<td>-0.16%</td>
<td>-0.22%</td>
</tr>
<tr>
<td>2030</td>
<td>-0.15%</td>
<td>-0.12%</td>
<td>-0.17%</td>
<td>-0.13%</td>
</tr>
<tr>
<td>2035</td>
<td>-0.14%</td>
<td>-0.17%</td>
<td>-0.25%</td>
<td>-0.14%</td>
</tr>
<tr>
<td>2040</td>
<td>-0.23%</td>
<td>-0.27%</td>
<td>-0.39%</td>
<td>-0.23%</td>
</tr>
</tbody>
</table>

Source: own elaboration

The final exercise conducted concerned a sensitivity analysis with lower oil prices scenario – USD 80/barrel –, table 5 show the results. In general, a low oil price scenario postpones and absorbs the negative impact of a carbon tax. For instance, in 2020 all the carbon tax scenarios considered were not yet negative with respect to its BAU. Nevertheless, in future years the negative effect will take place: we don’t analyse 2040 for the inconveniences concerning the mean reversion of GDP in model M in the last period.

Table 5. GDP deviation with respect to BAU oil price $ 80/barrel

<table>
<thead>
<tr>
<th></th>
<th>Carbon tax without recycling</th>
<th>Carbon tax with recycling</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$10</td>
<td>$20</td>
</tr>
<tr>
<td>2010</td>
<td>0.16%</td>
<td>0.25%</td>
</tr>
<tr>
<td>2015</td>
<td>0.17%</td>
<td>0.19%</td>
</tr>
<tr>
<td>2020</td>
<td>0.16%</td>
<td>0.14%</td>
</tr>
<tr>
<td>2025</td>
<td>0.16%</td>
<td>0.13%</td>
</tr>
<tr>
<td>2030</td>
<td>0.06%</td>
<td>0.12%</td>
</tr>
<tr>
<td>2035</td>
<td>-0.04%</td>
<td>-0.01%</td>
</tr>
<tr>
<td>2040*</td>
<td>-0.01%</td>
<td>-0.08%</td>
</tr>
</tbody>
</table>

Source: own elaboration

Concerning wages, results are shown in table 4. Results are consistent with the previews GDP analysis: the low oil price scenario may absorb the negative effect of the carbon tax in
wages. In fact, in 2035 all scenarios show a positive value with respect to BAU. Values in 2040 are not analysed because of the inconveniences outlined before.

Table 6 Wage deviation with respect to BAU for given mitigation actions with different oil prices assumption

<table>
<thead>
<tr>
<th></th>
<th>Carbon tax without recycling</th>
<th>Carbon tax with recycling</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$ 10</td>
<td>$ 20</td>
</tr>
<tr>
<td>2010</td>
<td>0.00%</td>
<td>0.01%</td>
</tr>
<tr>
<td>2015</td>
<td>0.00%</td>
<td>0.03%</td>
</tr>
<tr>
<td>2020</td>
<td>0.03%</td>
<td>0.07%</td>
</tr>
<tr>
<td>2025</td>
<td>0.06%</td>
<td>0.03%</td>
</tr>
<tr>
<td>2030</td>
<td>0.07%</td>
<td>0.04%</td>
</tr>
<tr>
<td>2035</td>
<td>0.07%</td>
<td>0.11%</td>
</tr>
<tr>
<td>2040*</td>
<td>-0.04%</td>
<td>0.02%</td>
</tr>
</tbody>
</table>

Source: own elaboration

6 Conclusions

It was observed that a $50 carbon tax can reduce Colombian energy related cumulative emissions by 33% until 2045. In all the evaluated measures, the mitigation could be obtained from changes in the transportation sector (use of electric vehicles and metro systems) and in the power sector by the increase of non conventional renewable energies as primary sources (geothermal, wind and solar). In this exercise we did not considered the use of nuclear as source for electricity production (during the discussions of the mitigation action for the power sector, this option were rejected). Penetration of electricity in the transportation sector would be part of the least cost energy mix (baseline) if the oil price does not decline from its current level: it would be too expensive otherwise. Part of the coal used currently in industries might be substituted by natural gas in presence of a carbon tax. With the evaluated measures, there is always a share of the industrial energy requirements that are met by using coal. The energy mix in commerce and households is not likely to change in the presence of the evaluated measures. It was observed that recycling mechanism have not significant results neither in the abatement potential nor in the resulting energy mix. Results are similar among the different taxes with and without recycling mechanisms.

Concerning the results of the model, there are two main conclusions of imposing a carbon tax. First, a carbon tax reduces GDP with respect to the business as usual scenario. The mechanism through which this tax reduces GDP is that as energy cost rise, the economy as a whole will have less money to spend on either consumption or investment, lower investment translates into a smaller capital stock, and less GDP growth. Second, the carbon tax impact on GDP can be reduced by transferring the collected money to the households. Yet, carbon tax with transfers still has a negative effect on GDP. In other words, “there is no free lunch” in mitigating GHG emissions with a carbon tax.

Following the suggestions made by the peers, it is important to develop further the first methodological approach presented in this document. This approach has several advantages,
mostly in the identification of sectoral impacts. Due to current structure of the models used by Uniandes and DNP to follow the first approach it is necessary to modify the structure of the MEG4C and to disaggregate the industrial sector description in Colombian Markal. Since Transaction costs involved in the collection and redistribution of the collected tax were omitted, there is the need to include these costs in the models in order to refine the outputs. The same is also a need regarding to the costs of measure and monitoring a limit on emissions.
7 References


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