A case study on Colombian mitigation actions

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A case study on Colombian mitigation actions

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This paper introduces the Colombian case study developed under the Mitigation Actions Plans and Scenarios Initiative and the Endesa Colombia Electric Vehicles Initiative. It is aimed to consider the use of electricity in the transportation sector, particularly in the city of Bogotá, Colombia. A model for assessing the economic and environmental impacts of the introduction of electric vehicles for private, utility and public services is proposed. Diversification of the energy basket by introducing electricity in the transportation sector is a plausible development strategy for the country. Colombian electricity is relatively clean because of the high hydro component in the generation basket; therefore the substitution of fossil fuels for electricity represents net savings in emissions of greenhouse gases as well as a reduction of particulate matter. The increase in electricity demand as a result of this new use is not high enough to stress installed generation capacity or supply security.

Keywords: nationally appropriate mitigation actions; electric vehicles; transportation models; emissions reduction

1. Introduction

Historically, developing countries have been responsible for only a small share of the world total greenhouse gas (GHG) emissions (Baumert, Herzog, & Pershing, 2005). In contrast, in the coming years, emissions are expected to grow faster in developing countries (DOE & EIA, 2011). In this context arises one of the most complicated challenges of global climate policy: to follow low-carbon-development paths. On the one hand, developing countries are trying to reach economic prosperity as fast as possible; on the other hand, costs and availability of clean technologies may slow down the economic growth, leaving as cheaper and available alternative the use of traditional dirty technologies (Cadena et al., 2011).

As response, the international community has been working on mechanisms to support the abatement of GHG emissions in developing countries. The implementation of Nationally Appropriate Mitigation Actions (NAMAs) in the context of sustainable development is one of those mechanisms (UNFCCC, 2007). ‘Nationally appropriate’ entails that its implementation contributes to the development goals stated by local policy. Those measures might be implemented by a developing country supported by the international community, considering that countries have common but differentiated responsibilities regarding climate change (United Nations, 1992).

The issue of climate change is on the Colombian policy agenda. The country joined the United Nations Framework Convention on Climate Change (UNFCCC) in 1994 and signed the Kyoto protocol. More recently, and following the guidelines of the National Development Plan (NDP) 2010–2014 (NPD, 2011), the Council of Economic and Social Policy (CONPES) presented an official policy report to establish the institutional arrangement that facilitates and enhances the formulation and implementation of programmes, incentives and projects on climate change (Council of Economic and Social Policy [CONPES], 2011). Four strategies were signalled: the National Adaptation Plan, the National Strategy for Reducing Emissions from Deforestation and Forest Degradation, the Strategy for Financial Protection against Disasters and the Colombian Low Carbon Development Strategy (CLCDS). The CLCDS is the most relevant in this case because it aims at identifying mitigation actions, including its abatement potentials and costs, to design sectorial mitigation plans and to implement them. Therefore, the CLCDS supports the formulation of NAMAs in different sectors, but until the date urban electric transportation is not part of the most prominent NAMAs (Colombian Low Carbon Development Strategy [CLCDS], 2013).

The use of electricity from renewable sources in the transportation sector could be an important measure to reduce GHG emissions and at the same time may contribute

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to one of the Colombian energy policy objectives which aims to diversify the energy consumption baskets. In that context, this paper aims to contribute with the characterization of that measure by two ways: the first one is to propose a methodological approach to assess the economic and environmental aspects of the use of electricity in the transportation sector; the second one is to perform a case study for the biggest city of the country in order to identify and characterize a possible NAMA (s) that might be implemented.

In particular, the proposed valuation methodology relies mainly on the Model for Economic and Environmental Assessment of Electric Vehicles (MEEAVE) that was developed to assess the economic and environmental impacts of the introduction of electricity as an energy alternative to meet the transport needs of a region. This model allows to compare the costs faced by demand to meet its transport requirements with several fuel baskets in the different transportation modes (i.e. taxis, private passenger vehicles, public transport and cargo service). At the same time, the model allows to estimate the mitigation of GHG and particulate matter (PM), the changes in the electricity and fossil fuels consumption and the sales or fleet paths that must be followed in order to reach a proposed penetration goal. Results from the case study allow to identify the economic savings of electricity penetration in taxis and small urban freight services. On the other hand, private passenger vehicles and buses imply additional costs for fossil fuels substitution. The former represents the biggest opportunity for GHG mitigation among the different transportation sectors in Bogotá and the latest is the only service that could be centrally planned by major companies or by the city’s administration.

This document has four sections hereafter. The first one briefly presents the Colombian energy and emissions situation, focusing on the transportation sector. The following two sections present the MEEAVE model and the case study for the city of Bogotá. Finally, the last sections are used to interpret and analyse the results and to present the final conclusions.

2. Energy and emissions context

This section contains a brief overview of the Colombian energy and GHG emissions context, with special emphasis on the transportation sector. Summarizing, Colombia has enough fossil fuel reserves and renewable resources (most of them hydro resources) to support its development process for the next years; energy is the second largest GHG emission sector and transportation is the main energy consumer, implying that it is mainly responsible for the emissions associated with the use of energy in the country.

In 2011, the country had proven oil reserves totaling 1.4 billion barrels, 60% of which were light oil (Energy and Mining Planning Unit [UPME], 2005). Proven reserves of natural gas in 2008 were 4.5 Tera cubic feet (Promigas, 2010). Regarding coal, the proven reserves in 2010 were 6814 million tonnes (British Petroleum, 2011). Colombian electricity generation is characterized for having an important hydro component that in 2011 produced 78% of the total national electricity (UPME, 2012). Colombia is the third largest regional consumer of hydropower after Brazil and Venezuela (British Petroleum, 2011), and has a theoretical hydro potential of 90,000 MW. The Colombian generation basket is complemented primarily with natural gas, to a lower extent with coal and some marginal participation of other type of plants (biomass and wind power plants). Moreover, the electricity sector experienced a reform in the early 1990s that enhanced the robustness and reliability of the supply of electricity.

Final energy demand in Colombia was 962.3 PJ in 2010 and the transportation sector accounted for 38% of that energy. Diesel is the main fuel used in road transportation followed by gasoline; by national regulations, both of them contain a percentage of biofuel (ethanol for gasoline and biodiesel for diesel). Compressed natural gas (CNG) was initially used only by public urban passenger transportation vehicles (taxi cabs and buses) and in recent years there has been an increasing number of vehicle conversions (automobiles and small trucks) from gasoline to CNG due mainly to high oil prices. As a result, CNG consumption has increased.

Other important changes that have taken place recently are the net increase in the automotive fleet and the incorporation of some bus rapid transit (BRT) systems in the main urban centres of the country. In 2010, there were approximately 3.6 million vehicles of which freight represents 6.7% and passenger transportation the remainder.

In local pollution, urban transport has been identified as the main cause of air pollution in urban centres of the country, this being the problem with the higher environmental and social costs associated, after water pollution and natural disasters (MAVDT, 2011). As a consequence, the government has made efforts to achieve the reorganization and optimization of the transport service. With respect to electric transportation, Decree 2439 of 2010 granted a tariff reduction for the import of clean technology vehicles, which applies to hybrid, electric and dedicated natural gas vehicles; and Decree 677 of 2011 ordered measures to encourage the use of electric vehicles in Bogotá and promote a pilot project for taxis during three years.

Estimations performed by Universidad de los Andes indicate that the scenario without constraints would lead to a fleet with 7.3 million vehicles and 9.4 million motorcycles in 2030. The forecast for population in that year is 56 million inhabitants (Echeverry Bocarejo, Acevedo, Lleras, Ospina, & Rodríguez, 2008). Currently, the rate of vehicles per 1000 people is 130, which is small compared to many other countries. On the other hand, the number of buses per person in the main cities of Colombia
According to Colombian Institute of Hydrology, Meteorology and Environmental Studies (Institute of Hydrology, Meteorology and Environmental Studies [IDEAM], 2009), the total GHG emissions in the Colombian transportation sector for 2005 were 20,000 Gg CO₂e. In 2004, energy use was responsible for 36.65% of the national emissions as can be seen from Figure 1. This sector is the second largest emitter of GHG in the country. Within the energy module, transportation contributed with 33% of the total emissions. The automotive subsector has the biggest share in the transport emissions, in 2004 emitting 89.5% of total emissions. Passenger transport is responsible for about a half of all emissions within the automotive subsector, of which about two-thirds are related to the urban passenger transportation. The above shows that urban passenger transportation (public and private) carries the main responsibility for the emissions of one-third of the total emissions of the energy module, which means 12% of the national emissions in 2004. In that order of ideas, in search of GHG abatement opportunities, the urban transportation sector should be considered as it is one of the main emitters within the Colombian context and it might also have some of the biggest abatement potential.

### 3. Methodological proposal. Model for economic and environmental assessment of electric vehicles – MEAVE

In order to perform the evaluation raised in this article, it is of paramount importance to review and take into account some of the models that have been implemented and are focused on the forecast and evaluation of electric vehicles. The models above can be classified into three broad categories, namely simulation, accounting and optimization. The simulation models are intended to analyse the behaviour of a system under certain initial conditions and parameters defining time variations. Accounting models focus on the quantitative estimation of parameters of environmental, economic or energy nature, affected by various inputs in a given time horizon; with these models, it is possible to synthesize the results by using statistics and also to identify relationships and dependencies. Optimization models compare various cases and determine the optimal value by considering some selection criteria.

By reviewing literature, various modelling options were found, whose features are quite extensive. Some of the models and software applications identified are: ADVISOR – ADvanced Vehicle SimulatOR – which implements a simulation and optimization model utilized for the analysis of performance, fuel economy and emission of conventional, electric, hybrid and fuel cell vehicles (Gao, Mi, & Emadi, 2007); Powertrain System Analysis Toolkit is simulation software that allows to structure the basic vehicle characteristics and select different configurations, predicting in an accurate way the fuel economy and performance (Gao et al., 2007); Long-range Alternatives Planning System is a software tool utilized to approximate energy consumption, production, resource extraction and emissions of local and regional air pollutants in all economic sectors (COMMEND) and it has been the primary tool (accounting model) used for the modelling of the penetration of electric vehicles in Thailand (Saisirirat Chollacoop, Tongroon, Laoonual, & Pongthanaisawan, 2013), by considering the changes in the behaviour of the load curve for electricity demand from vehicles; LEAP has been used in another case presented in Juan González (2012), where scenarios were developed to analyse the evolution of light-duty vehicle fleet in Colombia under different choices regarding powertrains, fuels and materials for vehicle manufacturing; a simulation model called VECTOR21, which compares scenarios, technologies and components, includes 3 sizes of vehicles, 10 types of technologies and 900 different users with defined preferences regarding vehicle attributes. The scenarios developed are intended to assess the impact of these vehicles on the market and it has been validated with historical information from the passenger fleet in Germany (Propfe, Kreyenberg, Wind, & Schmid, 2013); the Energy Economics Group of the University of Technology analyses the effects of policy, fuel prices and technological progress on the Austrian car fleet’s energy consumptions and GHG emissions using an accounting model mathematically described in (Kloess & Müller, 2011); the University of Paris developed an accounting model to estimate environmental and economic trends that promote electricity to be used as alternative fuel in vehicles (Prud’homme & Koning, 2012); another accounting model was developed in the University of Oxford, called Transport and Carbon Simulation Model and it functions as an interactive game where the objective is focused on reducing emissions in the transport sector. This model considers the implementation of alternative fuels, policies, prices, differences in emissions on vehicles and different user roles (‘free riders’, ‘techno-optimist’, ‘enviro-optimist’ and the like). In (Hickman, Ashiru, & Banister, 2010) different packages or combinations that reduce and compare the levels of contamination are addressed and, finally, the International
Energy Agency – has a roadmap that includes a MARKAL model to identify the optimal conjunction of technologies and fuels to meet energy demand, taking into account constraints such as the availability of resources (Australian Energy Market Commission [AEMC], 2012). The model and the technique used in each analysis depend on the objectives of the study, the accuracy of the information and the flexibility of the interface used to enter data, simulate and analyze results.

In Colombia, the variety of models for assessing aspects of electric vehicles is not very extensive. A study case has been developed in the LOGIT model, a simulation model where the comparison of technology attributes (colour, price and performance) determines the probabilities of choice. Consequently, the impact on energy demand when penetrating electric and hybrid vehicles in the Colombian fleet is estimated (Zapata, 2009). The National University of Colombia used the MARKAL model to optimize technological participation with information based on demand and economic, energy, environmental and technological parameters (Universidad Nacional de Colombia – Sede Medellín, 2007).

MEEAVE emerges as an alternative model evaluation against electric vehicles, providing the user with a global perspective that includes the main technical, environmental, economic and energy features associated with the transportation sector. MEEAVE is composed of a friendly graphical interface and its concrete structure offers the possibility of prospective evaluations and comparisons between vehicles of different technologies, adjustable to any segment of the vehicle fleet or transportation system of any city.

3.1 Model for Economic and Environmental Assessment of Electric Vehicles

MEEAVE (acronym in Spanish for ‘Model for Economic and Environmental Assessment of Electric Vehicles’) was developed in this study in order to assess the penetration of electric vehicles in the road transportation sector. MEEAVE is an accounting model that was designed and built aiming to support decision-making processes tied to a specific set of modelling considerations agreed upon after discussions with decision-makers of some private electricity utilities and relevant public entities such as MADS and the Bogota’s secretary office of transportation. Among the main modelling considerations assessed by MEEAVE are: electric vehicles technology is still under development, so prices are expected to decrease; it is desirable that the model allows to evaluate different types of goals and penetration trajectories of the new technology in a simple manner to facilitate comparison between measures; energy prices and electricity-emission factors might change during the evaluated period; sales are due to the requirements to replace scrapped old vehicles and increase the net fleet; batteries in electric vehicles represent an important share of full investment and it is expected that those vehicles may need to replace the batteries within their useful lifetime. Next, the structure of the model is summarized as well as the way in which some of the modelling considerations were addressed.

The model consists of five modules and allows an analysis in a time horizon of 30 years within a specific subsector (i.e. private vehicles, buses, taxis and light urban freight). The first module corresponds to the technical and economic characterization of the different transport technologies suitable for the relevant subsector. Vehicles are characterized by their main fuel; their investment and maintenance costs; average consumption and expected lifetime. As electric vehicle technology is still under development, it is expected that prices will decrease during the coming years; this module allows the incorporation of a changing technology price path and differentiating the prices of the vehicle and the required batteries.

In the second module, relevant energy sources are characterized by identifying their cost path and emissions associated with their use. Emissions associated with the use of electricity are nil, but there are some GHG emissions due to electricity production; those emissions depend on a specific electricity basket. Indeed, this module allows choosing whether or not GHG emissions associated with electricity production are accounted for; furthermore, the associated electricity emission factor might be modelled as a fixed value or, if major changes in the electricity basket are expected, as a yearly changing value.

In the third module, transportation demand to be met is characterized, and a baseline of technologies used to satisfy that demand is established. Demand is defined by the yearly fleet size and by the average mileage. Demand projection is an input of the model and must be calculated exogenously. As electricity may be part of the baseline (e.g. when there are ongoing pilot programmes) this module allows the inclusion of a share of electric vehicles on it.

The fourth module allows the determination and characterization of electric fleet penetration scenarios to be compared against the baseline. This is one of the most prominent differences between MEEAVE and other energy-accounting models: as this model was designed specifically to evaluate electricity penetration in transport, it allows the evaluation of different types of goals and penetration trajectories in a simple manner, and simultaneously considering the replacement of vehicles and batteries when they reach their useful period or a given number of changing cycles. The goal that is being sought can be expressed as a percentage of annual sales of new vehicles, the participation in new vehicle sales in the final year, the kilometres powered by electricity in a given year, the total fleet circulating in a given year or directly dimensioning the size of the electric fleet in each year of the study period. The selected goal determines the trajectory of the fleet in the scenario. In Section 3.1.1.1, each of the possible evaluating measures is introduced in greater detail. In this module, values for discount rate and for social costs of particulate material (PM) are chosen by the
user. Social costs of PM refer to an economic assessment of the impacts that PM has on public health and people’s productivity; that value differs from town to town and is exogenously calculated. MEEA uses a social cost of PM introduced by the user to assess the potential savings on public health and productivity reached by avoiding the emissions of those sorts of pollutants.

Finally, in the fifth module, results are shown. Some of the information presented in this module include; differences in costs to satisfy the demand between the baseline and the penetration scenario; energy consumption, disaggregated by type of fuel (including electricity); the reached abatement of GHGs and local pollutants (PM), yearly fleet and sales trajectory for each type of fuel.

3.1 Penetration goals

3.1.1 Kilometres travelled in the final year. It allows establishing the minimum participation of electric technologies in the useful demand (measured as kilometres travelled) of the transport service in a specific year. The trajectory of electric fleet (VEB) in year \( t \) is determined as the number of initial vehicles if \( t \) equals the initial year of the measure or from the following formula for the other years.

\[
\text{Electric fleet}_{t} = \text{Electric fleet}_{t-1} \times \left(1 - \frac{1}{\text{Useful life VEB}}\right),
\]

3.1.1.2 Participation in annual sales. It allows setting a goal of a minimum percentage of participation of electric vehicles in annual sales during the evaluation period.

\[
\text{Electric fleet}_{t} = \text{Electric fleet sales}_{t} + \left(\frac{\text{Electric fleet}_{t-1}}{\text{Useful life VEB}}\right) \times \text{goal} \times \text{total sales}_{t}.
\]

3.1.1.3 Participation in the final-year sales. It allows setting a goal of participation of electric technology in vehicle sales of the final year. This goal is reached after successive increases in the participation of sales from an initial value (0% participation of sales, currently).

\[
\text{Electric fleet}_{t} = \text{Electric fleet sales}_{t} + \left(\frac{\text{Electric fleet}_{t-1}}{\text{Useful life VEB}}\right) \times \text{goal} \times \text{total sales}_{t}.
\]

3.1.1.4 Participation in the final-year fleet. This goal allows the assessment of the cost and impact of a strategy seeking to have a certain number of electric vehicles circulating in a given year.

\[
\text{Electric fleet}_{t} = \text{Initial year vehicles} \times \exp \left[ \ln \left( \frac{\text{goal} \times \text{ICE fleet}_{\text{final year}}}{\text{final year} - \text{initial year}} \right) \right] \times \left(\frac{\text{current year} - \text{initial year}}{\text{current year} - \text{initial year}}\right).
\]

3.1.1.5 Penetration trajectory. It allows the establishment of an ad hoc trajectory of the size of the electric vehicle fleet in the scenario of each of the periods of the study horizon.

3.1.2 Mathematical formulation

The mathematical formulation of the model developed is introduced below. Set \( I \), composed of the different technologies that can be used to meet the transport demand of the category that is being studied (diesel, gasoline, dedicated natural gas, converted natural gas and electricity), is defined. The costs of the \( i \)th technology vary over time so it is important to identify the initial year of operation of each type of vehicle. Elements of set \( J \) are the years in which a determined technology vehicle can start operation. \( L \) is the set of recorded pollutants and \( T \) is the set of years that are being studied. It further has

\[
\begin{align*}
M & \quad \text{annual technology maintenance} \\
FU_{t} & \quad \text{usage factor in year } t \\
C_{i,t} & \quad \text{consumption technology } i \\
P_{i,t} & \quad \text{fuel price } i \text{ in year } t \\
r & \quad \text{discount rate} \\
II_{i,j} & \quad \text{initial investment technology } i \text{ in model } j \\
VU_{i} & \quad \text{useful life technology } i \\
S_{i,t} & \quad \text{share of technology } i \text{ in total annual sales of year } t \\
D_{i,t} & \quad \text{demand of technology } i \text{ in year } t \\
FE_{i,l,t} & \quad \text{factor of emission of pollutant } l \text{ in technology } i \text{ in year } t \\
m & \quad \text{cost for society of PM in the atmosphere}
\end{align*}
\]

Operation and maintenance costs of technology \( i \) in year \( t \) are given by

\[
\text{COM}_{i,t} = (FU_{t} \cdot C_{i,t} \cdot P_{i,t}) + M_{t}.
\]

The total cost of technology \( i \) entered in period \( j \) is calculated as

\[
C_{i,j} = \sum_{k=0}^{T} \frac{\text{COM}_{i,j+k} \cdot FE_{i,l,t}}{(1+r)^{k}} + II_{i,j}.
\]
with which the annual value of technology $i$, entered in period $j$, is obtained
\[
VA_{ij} = \frac{CT_{ij} \cdot r}{1 - (1 + r)^{-VU_j}}.
\]

The number of vehicles of technology $i$ entered in period $j$ and that are still in operation in year $t$ is
\[
f_{ij,t} = \begin{cases} 
0 & \text{si } j + VU_j < t < j \\
\left[1 - \frac{t-j}{VU_j}\right] & \text{si } j + VU_j \geq t \geq j.
\end{cases}
\]

The entry of vehicles of each $i$ type is given as a result of sales over a period of time. Total sales in period $t$ are calculated as
\[
VT_t = \sum_i \left(D_{i,t} - D_{i,t-1} + \frac{D_{i,t-1}}{VU_j}\right)F_{i,t},
\]
with which it is possible to quantify sales of technology $i$ in period $t$ as
\[
v_{i,t} = VT_t \cdot s_{i,t}.
\]

Thus, the annual costs of meeting the demand for transport of the category evaluated are
\[
CAT_t = \sum_i \sum_j f_{ij,t} \cdot VA_{ij}.
\]

And the total cost of meeting demand in the time period under study is
\[
CT = \sum_t \frac{CAT_t}{(1 + r)^{-g_t}}.
\]

Fuel consumption is necessary for estimating the emission of pollutants and is equivalent to
\[
CC_{i,t} = fu_{t} \cdot C_{i} \cdot \sum_j f_{ij,t}.
\]

Emissions of pollutant $l$ are estimated as
\[
E_l = \sum_t \sum_i CC_{i,t} \cdot FE_{i,l,t},
\]
with $l = 2$ we have the cost of the PM as
\[
CMP = \sum_t \sum_i \frac{CC_{i,t} \cdot FE_{i,2,t} \cdot m}{(1 + r)^{-g_{t}}}.
\]

with which finally the total system cost is obtained deducting the benefits obtained from savings of PM:
\[
CTC = CT - CMP.
\]

4. A case study: electric transportation for the city of Bogotá

For the specific case of Bogotá, a portfolio of electricity penetration in the transportation sector was designed and evaluated. For this purpose, urban transportation demand was divided into several categories: private transport, taxis, light-load fleet and Transmilenio mass transport system. For such categories, a specific goal was defined. Those goals as well as the main assumptions for the modelling process were agreed upon with Bogotá’s electric utility (Codensa) with some guidelines from the Energy and Mining Planning Unit (UPME), the Bogotá’s transportation secretary office and the MADS. The following subsections will elaborate further on the exercise performed: characterizing the technologies and the energy carriers considered, describing the demand for each sector, delineating the evaluated measures and presenting the obtained results.

4.1 Electric-transportation technologies and energy carriers

In order to evaluate the designed goals, we chose a standard vehicle that represents each category considered. Thus, each category is characterized by a single type of vehicle for each fossil fuel and by a single electric vehicle selected according to its characteristics in the currently available commercial cars. It is important to note that the information presented does not intend to advertise any brand of vehicles but corresponds to a selection made by authors based on a set of predefined criteria intended to find similar vehicles, in terms of capacity and body size, for each use category.

For private vehicles, two types of technologies were evaluated, private cars and station wagons. The car chosen as the standard for passenger cars is the Renault Fluence. The evaluation of the introduction of this type of vehicles in the fleet will take into account the participation of both, gasoline vehicles and converted from gasoline to natural gas vehicles. With respect to private station wagons, the vehicle selected is the Renault Kangoo. The technologies considered within the category mentioned above apply to vehicles using gasoline, natural gas (converted from gasoline) and diesel. Equipment considered in the evaluation of utility vehicles is the same as the one used to assess private station wagons; although as a result of their increased activity, annual maintenance costs for utility vehicles (cargo fleet) is 2.2 times the equivalent for the private station wagons. The technology selected for modelling gasoline- and natural gas-powered taxis circulating in the city is the Accent Vision model of Hyundai, and the equivalent electric vehicle considered is the E6 of BYD. Vehicles of the Transmilenio mass transport system were classified as articulated and standard. In both cases, diesel vehicles and electric vehicles were considered. For electric articulated buses we modelled catenary buses instead of
battery buses; infrastructure costs were not taken into consideration for the analysis.

Goals shown in next sections were assessed in three fuel-price scenarios. Those scenarios were built based on the considerations presented by the US Energy Information Administration (2011). It was assumed that the relative price of fossil energy sources remained constant throughout the study horizon. On the other hand, prices for electricity were assumed constant, considering that, during the following years, there are no expectations of major changes in the composition of the electricity basket, which is currently based on hydro and local fossil resources. The assumption that the electricity basket will remain constant in its composition is based on the fact that unexploited hydro resources in the country are enough to support the growing requirements. The above also implies that the emission factor associated with the electricity production will remain rather constant in comparison to the current value (UPME, 2010a, 2010b). The values for the emission factor for fossil fuels were taken from the database used in IDEAM (2009).

4.2 Evaluated portfolio

Transportation demand of the base year was estimated based on the number of trips generated in the city and taking into account the different modes of transport that supply that demand. In 2008, an average of 12.2 million daily trips were made in Bogotá (CCB-Unianes, 2009). Twenty-two percent of the trips were made by private transportation (light vehicles, all-terrain vehicles, station wagons and motorcycles), 23% by non-motorized means of transport (bicycle and walking) and 55% by public transport (taxis, Transmilenio mass transport system and conventional collective transport system – buses and minibuses).

The total travel demand was projected using the function of mobility ratio (number of trips/per capita) developed in a previous study for Colombia (Echeverry et al., 2008). The growth of the private vehicle fleet was modelled with the motorization rate (number of vehicles/1000 per capita) projected to 2040. In 2008, there were 129 vehicles in the city per 1000 inhabitants; for 2040, a rate of 490 vehicles per 1000 inhabitants was projected. According to a study conducted for 46 countries in the world (Dargay, Gately, & Sommer, 2007), the motorization rate in the USA, Canada, Belgium, Germany, France and Britain in 2002 was already higher than the value estimated for Bogotá in 2040. Moreover, the value obtained for Bogotá in 2040 is similar to what was shown in such study for Israel, México and Argentina in 2030. The average annual growth rate (of the motorization rate) obtained for Bogotá between 2008 and 2040 is of the same order of the growth rate of Brazil, Ecuador and the Dominican Republic for the period 2002–2030, according to the results of the aforementioned study. With the assumptions used, the number of private cars will grow at an average annual rate of 5.8%, which means that in 2040 there will be about five million private vehicles.

In the demand projection of the reference scenario for public transport was considered the demand of the Transmilenio mass transport system with future works (six new BRT corridors). Moreover, the implementation of the Integrated Public Transport System (SITP, for its acronym in Spanish), its demand goals, scrappage of buses and integration with new modes of transport in the city, such as the metro and the light rail were also taken into account (Colombian Comptroller’s Office, 2010; Econometría, 2007).

Finally, the projection of taxis and non-motorized modes of transport was estimated assuming that they gradually reduce their participation in city trips by 15%, following the rise of private transport and public transport provision. This is the projected reduction for these two modes for Bogotá in Echeverry et al. (2008). Values of annual mileage of the vehicles and fuel participation were obtained from a previous study developed for Bogotá (Universidad de los Andes, 2010a, 2010b).

In that context, a set of goals for each of the categories considered was formulated according to the market expectations perceived by experts of Endesa in Colombia. For the case of public buses, and considering that changes in the fleet (replacements or increase of the fleet) occur only in discrete periods, a trajectory that coincides with the expected expansion of the system was proposed, assuming that these expansions are made only with electric vehicles. For the other categories of vehicles (i.e. particular vehicles, freight and taxis), we set a goal of participation of electric vehicles in the final-year fleet, starting penetration in 2020. Values for that goal were defined to be 30% in taxis and light-load fleets and 15% in private cars. Next, results from assessing those goals using MEEAVE are presented.

4.3 Quantitative results and qualitative analysis

This section presents the main quantitative results of the case study. As one of the objectives of this study is to identify and characterize a possible NAMA that might be implemented, quantitative results are complemented with a qualitative analysis regarding actions required to allow reaching the identified abatement potentials as well as some guidelines aimed for a measurement, reporting and verification (MRV) system in the Colombian context.

Table 1 summarizes the main results obtained by modelling the proposed penetration portfolio. Those results will be further analysed in this section. Presented results are those obtained considering the intermediate scenario of fuel prices. Values for CO₂ abatement were calculated considering the increase in emissions due to increase in electricity production.
Figure 2 shows, as example, the conformation of the fleet of utility vehicles to a penetration goal of 30% in 2040; other categories present similar behaviours. That penetration contrasts with the behaviour of GHG emissions that are shown in Figure 3. As can be seen, before 2030 emissions of GHG reduce their growing rate but after that emissions reverse their growing rate. This is a very interesting result that reveals that in Colombia, due to the low emission factor in electricity production, a 30% of participation of electricity in the fleet decreases not only the growing rate of GHG emissions but also their absolute value in most of the categories. For example, freight fleet emissions in 2040 are less than emission levels reached in the same scenario (with electricity penetration) by 2032, which means that GHG emission growing rates during the last years were negative.

Electricity consumption due to electrical transport penetration is presented in Figure 4. The maximum electricity consumption of the modelled sectors is reached in 2040: 2108.3 GWh-year. Considering that total demand for electricity in Colombia during 2010 was close to 52,000 GWh-year, it can be seen that the additional demand corresponding to electrical transport in Bogotá would be a small fraction of the national annual demand. In fact, consumption of modelled vehicles in 2040 represents 4% of the Colombian electricity consumption in 2010. In other words, the Colombian power sector will be required to increase its generation by a total of 4% in 30 years in order to fulfill the transportation demand in Bogotá; that requirement could be satisfied easily by Colombian power sector without modifying its electricity basket. On the other hand, it still has to be considered how the additional demand is distributed throughout the day to assess the impacts that apparently seem insignificant in the transmission and distribution networks.

As mentioned above, substitution of natural gas and oil derivatives for electricity implies reduction of GHGs in Colombia, even considering the additional emissions caused by the increase in the country’s electricity generation. Figure 5 shows the reductions of GHGs achieved by using the amounts of electricity presented in Figure 3.
to replace natural gas and oil derivatives in transportation in Bogotá. By 2040, those reductions would represent net savings of 15.3% compared to the baseline (without electricity penetration). In all cases, the reduction of PM is at least equal in proportion to the reduction of GHGs, with corresponding savings in terms of health for society in general. It is interesting to note that, despite the fact that private transport has a lower level of annual activity, its consumption and reduction potentials are significantly higher than those of other types of transport. This can be explained by the differences in the sizes of the fleets in each type of service.

A summary of the economic analysis of the different measures can be seen from Figure 6. It can be seen that there are three main groups in relation with the cost effectiveness of the measures: non-regret measures (taxis and freight), ‘affordable’ measures (private vehicles and articulated buses) and ‘expensive’ measures (regular BEV buses). Light-load fleets and taxis show that penetration of electricity implies savings. In these two categories, due to its high utilization, fuel costs are a major component in the total cost structure of the service, so that savings from the use of electricity as fuel (knowing that this energy source is much cheaper and efficient than fossil fuels) compensates the differential value of the initial investment when buying an electric vehicle instead of a cheaper conventional car.

If considered, savings associated with avoided PM increases by 40% the savings by the introduction of taxis and decreases by 26% and 32% the additional costs of use of electricity in private cars and station wagons (as shown in Table 1). On the other hand, the same concept modifies the total costs of benefits in the other sectors by less than 5%.

These results are heavily dependent on oil prices, as shown in Figure 7. In a scenario of future high prices for oil, almost all measures (except the regular buses of the mass transport system) represent monetary savings and emission reductions. In opposition, in the low oil price scenario, abatement costs exceed in most cases $50 per tonne of CO2 avoided and no measure represents financial benefits. In all cases, again, the effect of considering the social cost of the PM is to decrease the costs of the electric vehicle penetration programme.

An electricity penetration portfolio, as the one proposed here, may be considered an appropriate mitigation action.
Electric vehicles are a plausible development strategy for the country considering that diversification of the energy basket has benefits in terms of security of supply and that PM reductions have positive impacts in the population health (and its productivity); furthermore, the increase in electricity demand as a result of using this energy source in transport does not seem to be important from the point of view of requirements of installed generation capacity. As Colombian electricity is generated (and it is expected that it will continue being generated) mainly from renewable sources, its use replacing oil derivatives and natural gas in transportation allows GHG abatements calculated in this study.

However, there are some barriers that must be overcome in order to allow measures like those proposed in this paper to become reality. The first of them is related to infrastructure requirements such as charging stations. Penetration of electric vehicles can be delayed due to the lack of public charging stations or due to the costs of the home charging stations. The second barrier is related to economic aspects. Results from the model identify the economic benefits of electricity penetration in taxis and small urban freight services; savings on fuel are enough to offset the initial investment costs. However, while additional investment costs must be faced at the time of buying the vehicle, savings are reached throughout the vehicle’s useful life. This barrier could be overcome by enabling lines of credit for the down payment. On the other hand, private passenger vehicles and buses imply additional costs. Private passenger vehicles represent the biggest GHG mitigation potential. Their mitigation potential can be used to obtain financial support in order to reduce the gap between the traditional internal combustion vehicles and the electric ones. Finally, electricity use in the public massive transportation system is the most expensive alternative and does not have a significant GHG mitigation potential. In contrast, that is the only transportation sector that could be centrally planned by major companies (bus owners or Transmilenio) or by the district administration, so its implementation might be defined by political initiative.

Thus, a NAMA to incentivize electricity penetration in Bogota’s transport sector may be structured to find financial support in order to overcome the barriers mentioned above (or others). In any case, a NAMA requires the implementation of a MRV system. Next, some guidelines about those requirements will be shown in order to contribute with a starting point for a possible NAMA that might be implemented to support the electrification of Bogota’s transportation looking for the GHG abatements identified in this study.

4.3.1 Guidelines for an MRV system for a possible electric vehicles NAMA for Bogota

MRV systems are considered as fundamental in NAMA’s context (Fransen, 2009; McMahon, & Moncel, 2009). Despite the MRV systems not yet being defined by the UNFCCC, some approaches to MRV systems have been proposed by different authors (Clean Air Asia, 2011; Center for Clean Air Policy, 2011, 2012; Fransen, 2009; Fukuda, 2009; GIZ, 2013; Höhne, Jung, Ward, & Effermann, 2007; McMahon, & Moncel, 2009; Tilburg, Röser, Hänself, Cameron, & Escalante, 2012).

An MRV structure could be based on the existing verification system that the Colombian government uses in order to verify the accomplishment of the goals proposed in the NDP. Within this scheme is the SIGOB, which is an information system implemented by the National Planning Department and the Presidency. It consists of verifiable numerical targets and indicators. The evaluation of the NDP is reported periodically to ministries, administrative departments, sector agencies, council of ministries, the National Planning Council and the National Congress (NPD, 2010a, 2010b). For specific indicators, we found useful the National Traffic Unique Registry (RUNT) from the Transport Ministry and some of the reporting and verification systems that are currently in use in institutions, for example, the ones used for the accomplishment of ISO standards (e.g. 9000 or 14,001).

Considering the mitigation measures previously analysed, some indicators were selected. Tables 2–4 introduce

<table>
<thead>
<tr>
<th>Type of indicator</th>
<th>Indicator</th>
<th>Units</th>
<th>Responsible entity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Implementation</td>
<td>Number of electric vehicles in public transport systems</td>
<td>Number of vehicles/year</td>
<td>Transport Ministry</td>
</tr>
<tr>
<td>Implementation</td>
<td>Number of electric vehicles in taxi fleets</td>
<td>Number of Vehicles/year</td>
<td>Transport Ministry</td>
</tr>
<tr>
<td>Implementation</td>
<td>Total electric vehicles registered each year</td>
<td>Number of vehicles/year</td>
<td>Transport Ministry</td>
</tr>
<tr>
<td>Monitoring</td>
<td>Energy intensity of the urban public transport sector (including BRTs)</td>
<td>MBTU/(passenger-Km) or GWh/(passenger-Km)</td>
<td>National Energy Planning Unit, BRT companies and Transport Ministry. The indicator could be built by the Environment Ministry</td>
</tr>
<tr>
<td>Monitoring</td>
<td>Passenger Kilometres Index in electric BRT systems</td>
<td>Passenger/kilometre</td>
<td>BRT companies and the Transport Ministry</td>
</tr>
</tbody>
</table>

Source: Prepared by the authors.
different electric modes. Finally, different electric model allows estimating transportation demand for different paths for energy carriers considered in the model. The technologies as well as prices and environmental emission drives the user through different strategies to reach penetration goals. Its modular configuration drives the user through five different modules starting with a detailed techno-economic representation of vehicles technologies as well as prices and environmental emission paths for energy carriers considered in the model. The model allows estimating transportation demand for different road modes. Finally, different electric fleet penetration scenarios can be evaluated: as a percentage of new vehicles sales or total circulating fleet, as a target of total kilometres travelled with electricity power or replacement of existing vehicles and batteries, or directly dimensioning the size of the electric fleet in each year of the study period. The selected goal determines the trajectory of the fleet in the scenario. Results are displayed in a simple manner: differences in energy consumption, costs, GHG and PM emissions to satisfy the demand between baseline and the penetration scenario as well as yearly fleet and sales trajectory for each type of fuel.

Results from this study were used to conceive a pilot programme for the city of Bogota. A portfolio of electricity penetration in the transportation sector was designed and evaluated. Results drive ENDESA and the MADS to start structuring a NAMA under the Mitigation Actions Plans and Scenarios Initiative. NAMA is an interesting alternative, taking into account the country’s context, the goals of the NDP and the Energy Plans. Electric vehicles are a plausible development strategy for the country. Colombian electricity is relatively clean; therefore, substitution of fossil fuels by electricity represents net savings in emissions of GHG in the country. Even though, the increase in electricity demand as a result of using this energy source in transport does not seem to be important from the point of view of requirements of installed generation capacity, the diversification of the energy basket has benefits in terms of security of supply.

As far as the NAMA proposal is concerned, we can say that the exercise of structuring a NAMA from scratch is not an easy task. The identification of technology, the construction of base lines and the definition of scenarios were quite time consuming and required a wider participation of the utilities and national and local energy and environmental authorities. In this document, first steps required for the structuration of a NAMA were taken (i.e. identifying abatement potential, development benefits, economic costs and possible barriers for implementation) as well as a preliminary proposal for an MRV system.

One of the main limitations of the model is that, being of annual resolution, it does not allow the identification of daily charging patterns, which is critical from the point of view of the distribution network. It is suggested as future work to complement the model or use an additional tool in order to overcome that limitation. Another task to be assessed in the future refers to the identifi-

### Table 3. Indicators from National Development Plan.

<table>
<thead>
<tr>
<th>Type of indicator</th>
<th>Indicator</th>
<th>Units</th>
<th>Responsible entity</th>
</tr>
</thead>
<tbody>
<tr>
<td>NDP Programme: Environmental management and urban sector</td>
<td>Vehicles entering the fleet with cleaner technologies (natural gas, hybrids and electric vehicles)</td>
<td>Number of vehicles/year</td>
<td>Environment Ministry</td>
</tr>
<tr>
<td>NDP strategy: housing and friendly cities</td>
<td>Number of cities with urban mobility solutions in operation</td>
<td>Number of cities/year</td>
<td>Transport Ministry</td>
</tr>
<tr>
<td>NDP strategy: equal opportunities for social prosperity</td>
<td>Adjusted infant mortality rate, per 1000 born</td>
<td>Percentage</td>
<td>Social Protection Ministry</td>
</tr>
</tbody>
</table>


### Table 4. Additional monitoring indicator.

<table>
<thead>
<tr>
<th>Type of indicator</th>
<th>Indicator</th>
<th>Units</th>
<th>Responsible entity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sustainable development</td>
<td>Concentration of PM in urban centres where NAMA is implemented</td>
<td>µg PM$_{10}$/m$^3$</td>
<td>Environment Ministry</td>
</tr>
</tbody>
</table>

Source: Prepared by the authors.

the indicators with a brief description. It includes possible actors in charge of measuring and reporting them.

Even though information in the country is in general limited (National Administrative Department of Statistics, 2006), we considered that some of the existing systems are useful in reporting and monitoring indicators for an electric transport NAMA, at least as a starting point. Some indicators could be used just as they are designed, while some others can be estimated using data already being monitored. Moreover, using the existing systems in NAMA’s context can also contribute to overcome the actual limitations on information in the country, and this in turn may facilitate designing and implementing other low-carbon projects.

### 5. Conclusions

The model (MEEAVE) developed in this paper proved to be a flexible tool to evaluate different penetration targets of electric vehicles and useful to design the pilot programme for the city of Bogota. MEEAVE allows the user to consider different technologies as well as different strategies to reach penetration goals. Its modular configuration drives the user through five different modules starting with a detailed techno-economic representation of vehicles technologies as well as prices and environmental emission paths for energy carriers considered in the model. The model allows estimating transportation demand for different road modes. Finally, different electric fleet penetration scenarios can be evaluated: as a percentage of new vehicles sales or total circulating fleet, as a target of total kilometres travelled with electricity power or replacement of existing vehicles and batteries, or directly dimensioning the size of the electric fleet in each year of the study period. The selected goal determines the trajectory of the fleet in the scenario. Results are displayed in a simple manner: differences in energy consumption, costs, GHG and PM emissions to satisfy the demand between baseline and the penetration scenario as well as yearly fleet and sales trajectory for each type of fuel.

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One of the main limitations of the model is that, being of annual resolution, it does not allow the identification of daily charging patterns, which is critical from the point of view of the distribution network. It is suggested as future work to complement the model or use an additional tool in order to overcome that limitation. Another task to be assessed in the future refers to the identification of regulatory requirements and barriers that a portfolio like the one proposed in this document must face. Finally, the case study must be analysed vis-à-vis sensitivity to other parameters different from

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oil prices. In fact, the evaluated portfolio was only one of several portfolios considered and sensitivities were not further developed here because it was out of the scope of this paper, which aims mainly to present a methodological proposal and the evaluation of the most likely portfolio in the most probable scenario (according to criteria of Bogota’s electric utility and MADS experts).

References
Juan González, T.F. (2012). Low carbon road passenger
transportation system design using combined energy and
materials flows in Colombia. Sendai: Tohoku University.
Kloess, M., & Müller, A. (2011). Simulating the impact of policy,
energy prices and technological progress on the passenger car
fleet in Austria – a model based analysis 2010–2050. Energy
Policy, 39(9), 5045–5062.
report. Bogotá, Colombia: República de Colombia,
Ministerio de Ambiente, Vivienda y Desarrollo Territorial.
positions and design elements of an MRV framework. WRI
undpce.org/docs/UNFCCC%20negotiations/Countries%20posi
tions%20hand%20analysis/WRI_KeepingTrack_June2009.pdf
Colombian national strategic plan for statistics. Comunidad
org/eportal/contenidos/imagenes/file/pendes/docs/Cartilla_ Pendes_colombia.pdf
pobreza y más seguridad. Bases del Plan Nacional de
Colombia, Departamento Nacional de Planeación.
NPD. (2010b). Evolución de SINERGIA y evaluaciones en
administración del Estado. Bogotá: Dirección de
Evaluación de Políticas Públicas, Departamento Nacional de
sinergia/Archivos/Cartilla_UNO_Sinergia_Admin_Estado.
dpdf
Colombia.
NPD. (2011a). Un cuatrienio de oportunidades, crecimiento e
innovación. [Powerpoint slides]. Retrieved from https://
www.dnp.gov.co/LinkClick.aspx?fileticket=8g7YTLGNN0o
%3d&tabid=82
Prosperidad para todos. Bogotá: Departamento de
Planeación Nacional de Colombia.
com/wps/wcm/connect/84a9ad8048997f5aabf7ecbf9e50a54/
Informe+del+sector-2011.pdf?MOD=AJPERES&CACHEID=
84a9ad8048997f5aabf7ecbf9e50a54
Market penetration analysis of electric vehicles in the
German passenger car market towards 2030. International
economic and environmental evaluation. Transport
Policy, 23, 60–69.
Saisirirat, P., Chollacoop, N., Tongroon, M., Laounual, Y., &
Pongthanaisawan, J. (2013). Scenarios analysis of electric
vehicle technology penetration in Thailand: Comparisons of
required electricity with power development plan and projections
of fossil fuel and greenhouse gas reduction. Energy
Tilburg, X.V., Röser, F., Hänsel, G., Cameron, L., & Escalante, D.
(2012). Status Report on Nationally Appropriate Mitigation
Actions (NAMAs)-Mid-year update May 2012. ECN and
Annual_Status_Report_on_NAMAs - Update_May_2012.pdf
from http://www.un.org/documents/ga/conf151/aconf15126-
1annex1.htm
Universidad de los Andes. (2010a). Curvas de costo de abatimiento
de los Gases Efecto Invernadero- GEI y potenciales de
mitigación en el sector industrial colombiano. Segundo
Informe: Caracterización de la Industria Manufacturera, por
sectores y sub-sectores. Bogotá. Author.
Universidad de los Andes. (2010b). Plan decenal de
descontaminación del aire para Bogotá. Bogotá, Colombia,
ment_library/get_file?uuid=b5f3e23f-9c5f-40ef-912a-51a58
22da320&groupId=55886
Evaluación de alternativas para la planificación energética
sostenible de los sectores industrial y transporte del Área
Metropolitana del Valle de Aburrá. Medellín.
Energy Outlook.
Zapata, R.S. (2009). Impacto en la demanda de energía eléctrica
en Colombia debido a la penetración de vehículos híbridos-
electricos y electricos. Medellín: Universidad Nacional de
Colombia – Sede Medellín.