MARGINAL ABATEMENT COST CURVE DEVELOPMENT FOR BUILDINGS OF THE COMMERCIAL SECTOR IN COLOMBIA

THE AILEG PROJECT

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ACRONYMS AND ABBREVIATIONS

AILEG	Analysis and Investment for Low-Emission Growth
BAU	Business-as-usual (extrapolated baseline)
BEN	National Energy Balance
CFL	Compact fluorescent
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
DANE	National Department of Statistics (Spanish acronym)
ECDBC	Colombian Strategy for Low-Carbon Development (Spanish acronym)
GDP	Gross domestic product
Gg	Gigagrams (1,000,000,000 grams)
$GgCO_2/PJ$	Gigagrams of carbon dioxide per Petajoule (PJ = 1.0 x 10^{15} joules)
GJ	Gigajoule (10^9 Joules)
GHG	Greenhouse gas
HVAC	Heating, ventilation, and air-conditioning
IPS	Health Services Institutions
kWh/month/m2	Kilowatt hours per month per square meter
LEAP	Long-Range Energy Alternatives Planning model
LED	Light-emitting diode
LEED	Leadership in Energy and Environmental Design
LPG	Liquefied petroleum gas
$m^3/month/m^2$	Cubic meters per month per square meter
MACC	Marginal abatement cost curve
NAMA	Nationally Appropriate Mitigation Action
NPV	Net present value
PROURE	Rational and Efficient Use of Energy and Unconventional Sources Program (Spanish acronym)
SUI	Sistema Único de Información (Unique System of Information, hosted by the Superintendent of Public Services, which requires regulated utilities to submit standardized data online)
tCO_2e	Tons of carbon dioxide equivalent
UDLA	Universidad de los Andes
UNAL	National University (Spanish acronym)
UPME	Mining and Energy Planning Unit (Spanish acronym)
USAID	United States Agency for International Development

EXECUTIVE SUMMARY

AIM OF THE REPORT

This report is the result of an investigation that was conducted by the School of Engineering of the *Universidad de los Andes* (UDLA) in Colombia. It was conducted under the Analysis and Investment for Low-Emission Growth (AILEG) project, funded by the United States Agency for International Development (USAID). The research adopted the approach used by the Ministry of Environment and Sustainable Development and UDLA in the Colombian Strategy for Low-Carbon Development (known as ECDBC, for its Spanish acronym). Since 2011, one of the main objectives of the ECDBC has been to develop marginal abatement cost curves (MACCs) to identify cost-effective carbon mitigation options in agriculture, waste management, transport, and construction.

This study focused on the MACCs for the commercial building sector in three Colombian cities (Bogotá, Medellín, and Barranquilla). MACCs can help identify mitigation measures that save money by reducing energy consumption, production inefficiencies, or the costs of environmental damage. Some of these measures may require changes in economic policies or institutional arrangements that may be difficult to achieve. MACCs highlight greenhouse gas (GHG) mitigation measures that:

- Can produce net cost savings over the project lifetime (win-win options)
- Have higher abatement potentials
- Are more cost-effective than alternatives

This report aims to:

- Illustrate GHG reduction measures for three Colombian cities in different climate zones
- Show GHG mitigation opportunities in the commercial building sector in Colombia (hotels, hospitals, shopping centers, and office buildings)
- Demonstrate that many GHG reduction measures can save money while reducing GHG emissions
- Present some recommendations for policies that can reduce GHG emissions over the period 2010 to 2040

The research results should not be considered definitive, but instead as a departure point for further analysis of GHG abatement potential in the commercial building sector. The preliminary results indicate potential for the following estimated annual reductions in carbon emissions (measured in tons of carbon dioxide equivalent, or tCO_2e):

- 6,000 tCO_2e/year in shopping centers
- 45,000 tCO_2e /year in office buildings
- 1,600 tCO_2e /year in hotels
- 2,000 tCO_2e /year in hospitals

APPROACH

This report summarizes mitigation measures for four commercial building subsectors (hotels, hospitals, office buildings, and shopping centers) in Bogotá, Medellín, and Barranquilla. These three cities were selected because they are representative of the climate in Colombian cities. An emissions baseline for the period 2010–2040 was developed for each subsector. The mitigation measures were based on a group of building prototypes selected because they were representative and because information was available. The identified mitigation measures include architectural and materials isolation options; lighting options; heating, ventilation, and air-conditioning (HVAC) technologies; and energy building infrastructure improvements.

The Marginal Abatement Cost Curves (MACCs) were formulated after evaluating each mitigation measure in terms of capital expenditures, operating costs, and adoption rates for new and existing buildings. Additionally, the carbon dioxide (CO_2) mitigation potential was estimated for every option by considering data related to energy savings, implementation rates, and emission factors. Two sets of MACCs were generated. The first set considered the total implementation cost, while the second set only took into account the technology costs. The first approach was adopted because it provides a more coherent approach to MACCs. However, most MACC studies focus only on technology costs, and thus, that approach was also included in this analysis to facilitate comparisons between this and other similar analyses. Both sets were estimated with the same assumptions about operating costs and CO_2 reductions.

CONCLUSIONS AND RECOMMENDATIONS

Although 60 different measures were analyzed for each subsector, the individual MACCs present a maximum of 36. Certain options were excluded from different MACCs due to high capital or operating costs or low mitigation potential, which could dramatically increase the cost-per-ton index.

Lighting options were the most important measures in all four subsectors, due to their large mitigation potential and negative net costs for both new and existing buildings. Design-related measures had the highest capital or operating costs per ton of carbon equivalent in all four subsectors in the three cities.

There are important opportunities to mitigate GHG emissions in the sector by improving building and other assets management, including better practices during construction of the different types of buildings considered in this analysis. Design, build, and operate arrangements were most attractive to the developers interviewed during the preparation of this study, some of which were already implementing energy- and water- efficiency measures.

1. INTRODUCTION

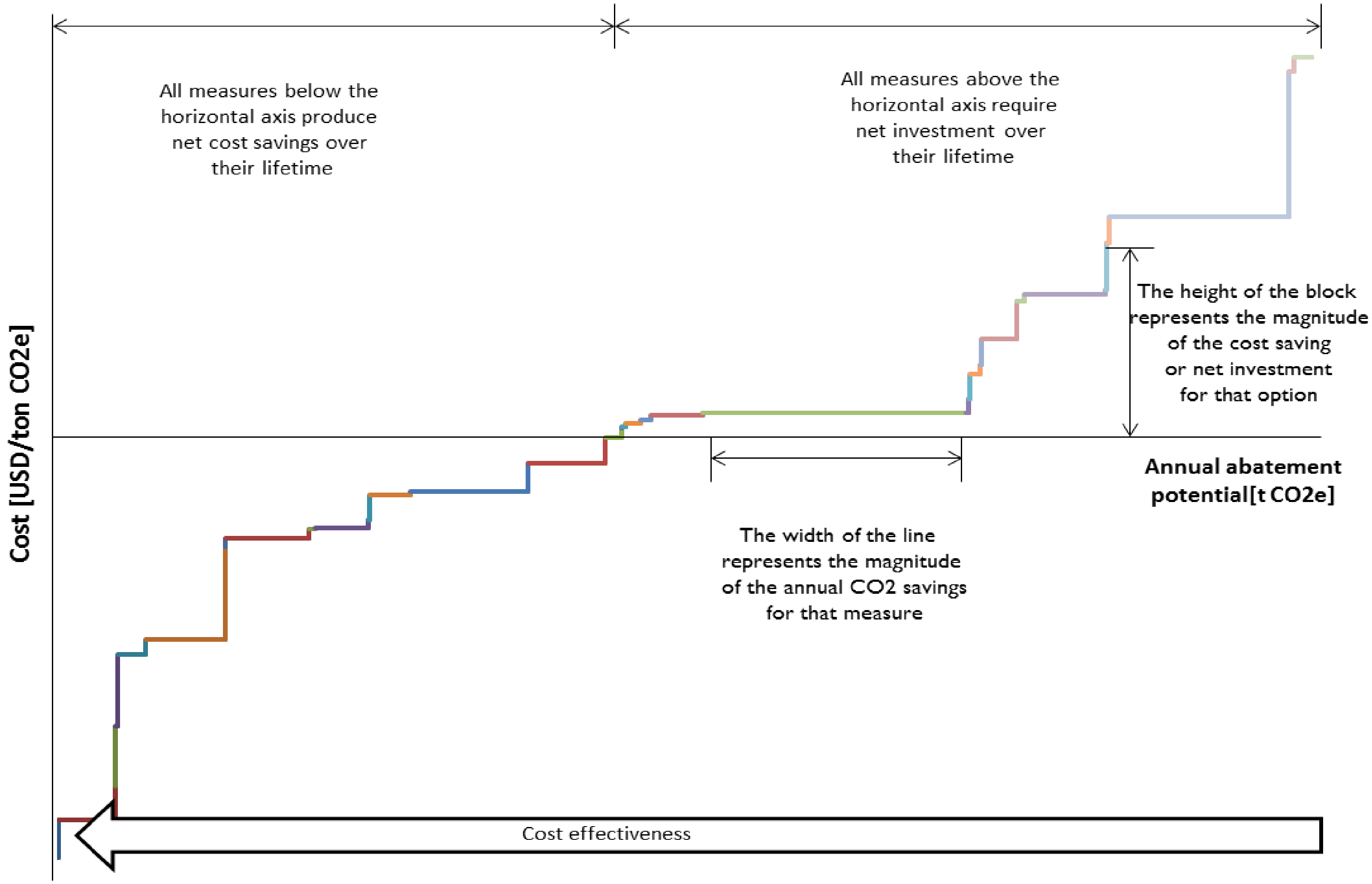
This document reviews the methods used to develop the MACCs for the commercial building sector in Colombia. The study includes an analysis of potential mitigation options to reduce GHG emissions by replacing conventional technologies with low-carbon strategies in four commercial building subsectors (hotels, hospitals, office buildings, and shopping centers) in three Colombian cities—Bogotá, Medellín and Barranquilla. The investigation was conducted by the UDLA School of Engineering in Colombia as part of the USAID-funded AILEG project. The research team adopted the approach used by the ECDBC.

This study provides an indication of the total potential for mitigation that could be achieved by implementing mitigation measures in the commercial building sector in Colombia. It also demonstrates that many GHG mitigation measures may save money and GHG emissions, and presents some recommendations for establishing policies to reduce GHG emissions during the period 2010 to 2040. Although these results should not be considered definitive, due to limitations in the data-collecting process, they may be seen as a first step towards identifying opportunities and highlighting important co-benefits for implementing low-carbon technologies.

2. A BRIEF ON MAC CURVES

A MACC compares the cost effectiveness of different GHG emissions mitigation measures in a single graph, which also shows the potential scale of emission reductions. Figure 1 shows how to interpret a MACC. The vertical (y) axis shows the cost-effectiveness ($\$/tCO_2e$) based on the net present value (NPV) of costs and lifetime GHG savings, while the horizontal (x) axis shows the annual carbon savings for each option. The cumulative annual savings (the width of all the rectangles) indicates the maximum potential carbon savings in a given year if none of the options are mutually exclusive. The total potential savings can be compared with the GHG emissions targets for the subsector, locality, or economy. The options in a MACC are presented in order of decreasing cost-effectiveness ($\$/tCO_2e$) (from right to left). Options below the horizontal axis can generate net cost savings over the project life (win-win options). Options with MACCs above the horizontal axis will require net investments.

Figure 1: MAC Curve Interpretation



3. MAC CURVES IN COLOMBIA: NEEDS AND CONTEXT

Colombia has relative low total greenhouse gas emissions, which constitute only 0.37 percent of the worldwide total (IDEAM 2010). However, public and private sector actors in the country have already begun to recognize the importance of mitigation actions to reduce the effects of climate change (Cadena 2008).

The Ministry of Environment and Sustainable Development began implementing the ECDBC in 2011. One of the first steps was the development of MACCs for energy production and distribution, solid waste, agriculture, industry, and housing developments. This was carried out in 2012 with support from the UDLA School of Engineering. The initial MACCs will be used to 1) establish guidelines for selecting priority mitigation measures to be implemented, and 2) to understand their associated costs per ton CO_2e (Cadena 2008).

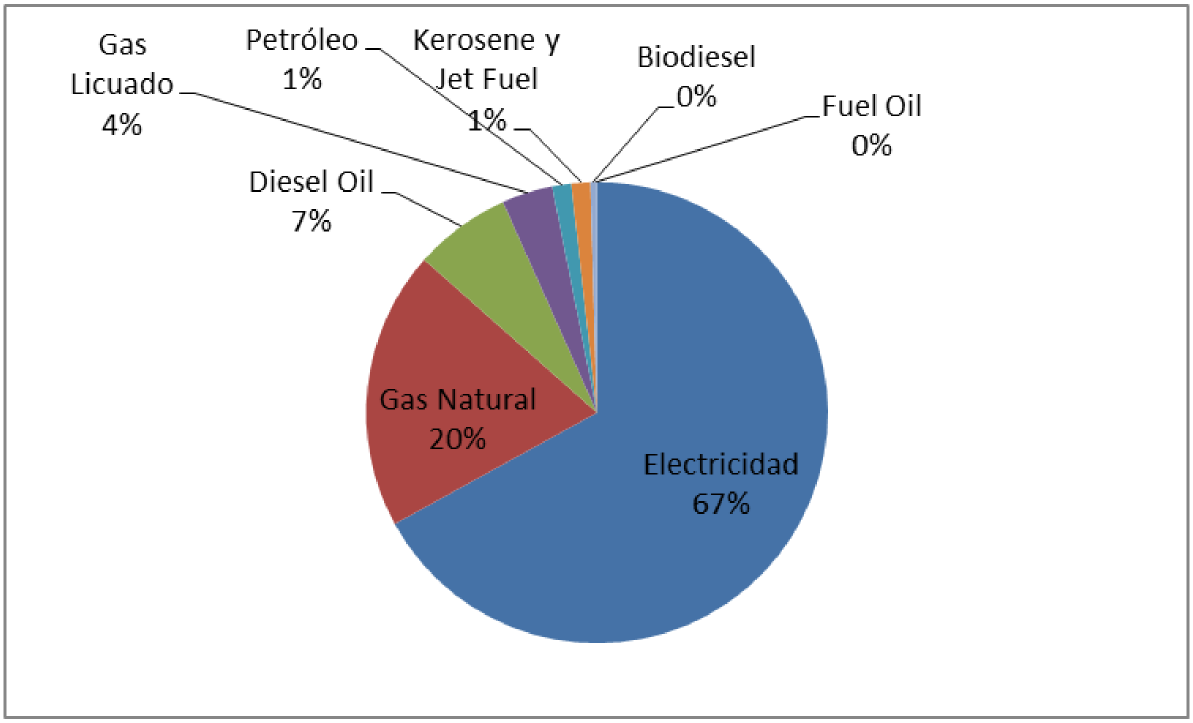
According to the Mining and Energy Planning Unit (UPME), the commercial and public sectors consumed 6.3 percent of the national power used in 2012; this proportion has remained constant since 2000. The services sector consumed the most electricity per consumer (67 percent of the total), based on a consumption of the following fuels: natural gas (19 percent), diesel (6.5 percent), and liquefied petroleum gas (LPG) (3.5 percent). According to the Institute of Hydrology, Meteorology and Environmental Studies (IDEAM 2009), the commercial and service sectors emitted 710 thousand tons of CO_2e in 2004, representing 1.08 percent of total national GHG emissions.

Together with the National University (UNAL), UPME studied energy consumption in the tertiary sector (education, health, commerce, hospitality, and public institutions) in 2007. This study found that the tertiary sector in Bogotá, Medellin and Barranquilla used between 29 percent and 30 percent of total national energy demand. However, there were considerable differences among the three cities. The financial sector consumed the largest percent in Bogotá (25 percent), while hospitals were the largest users in Medellín and Barranquilla. The study identified some potential energy efficiency improvements, including use of light-emitting diode (LED) or compact fluorescent (CFL) bulbs, reductions in lighting levels, and replacement of refrigeration and elevators.

UPME publishes the National Energy Balance (BEN) report, which presents the total annual energy consumption by fuel and by key economic sector. The latest BEN report (2009) stated that 87 percent of total energy consumption in the tertiary sector consisted of electricity and natural gas (see Figure 2). Since 1970, the fastest-growing energy sources have been electricity and natural gas (UPME 2010). In 1970-2009, electric energy consumption grew approximately 450% and the share of natural gas doubled, while diesel oil consumption did not grow substantially over this period, representing only 7 percent of energy consumption in the tertiary sector. Because of the importance of electricity and natural gas, this study focuses primarily on these two energy sources.

In 2010, the sources of electricity in Colombia included hydroelectric plants (67.4 percent), natural gas thermal plants (20.4 percent), and coal-fired power stations (7.3 percent). On average, 80 percent of energy sources in the country were renewable (UPME 2010). Figure 2 refers only to commercial and public sector energy usage at the national level, including consumption of electricity and fossil fuels. Fossil fuels were mainly used for cooking and water-heating (natural gas). Diesel oil and fuel oil were mainly used for back-up or emergency generators for buildings.

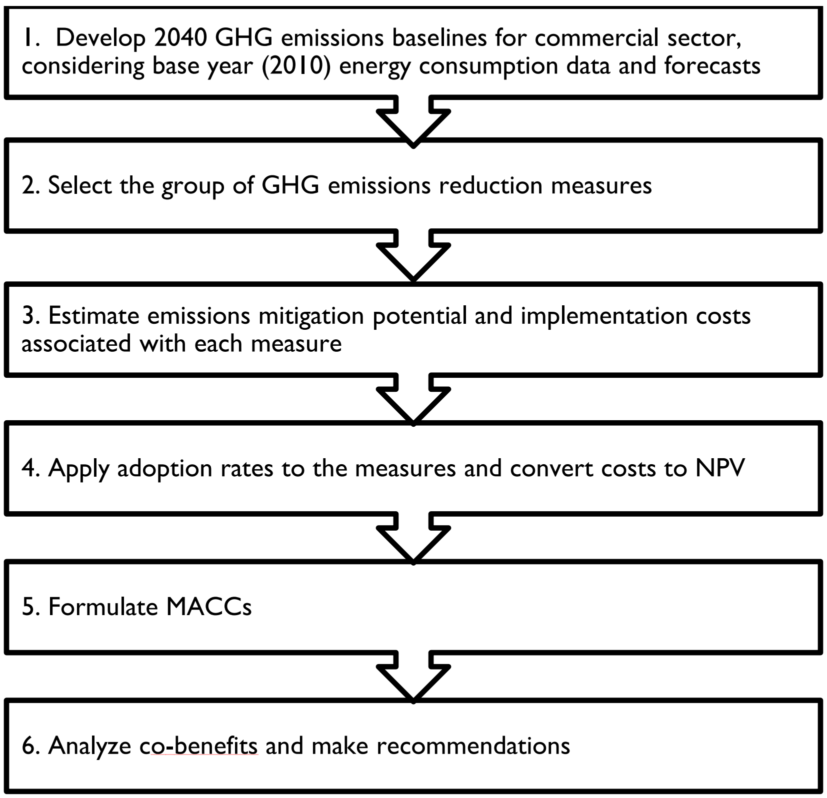
Figure 2: Energy Shares of the Commercial and Public Sectors at the National Level



Data source: UPME 2010

4. METHODS

Figure 3 summarizes the methods used in the study. Figure 3: Study Methods



4.1 ENERGY CONSUMPTION ESTIMATION IN 2010

4.1.1 Bottom-up Approach: Estimating Base-Year Consumption with Existing Data

The UPME (2007) study was used as a first estimate of commercial sector energy consumption and to characterize end-uses in each subsector. The study provided energy consumption estimates for different building types, using data from annual energy bills and direct measurements. The UMPE study differentiated between the shopping centers and the businesses in shopping centers. The UDLA team calculated consumption indexes for each building or commercial unit in kilowatt hours per month per square meter (kWh/month/m^2) for electricity and cubic meters per month per square meter m^3/month/m^2) for natural gas.

Table 1 summarizes average electricity and natural gas consumption indexes for the buildings or commercial units surveyed in the study.

Electricity consumption indexes are considerably higher for Barranquilla than Bogotá and Medellín (see Table 1). The largest differences are for businesses in shopping centers, where the difference between Barranquilla and Medellín is 30 kilowatt hours per month per square meter. The HVAC load in Barranquilla may be the reason for this difference, since this city has the highest ambient temperatures. Bogotá has the highest gas consumption per square meter, followed by Barranquilla and Medellín. Bogotá has the lowest ambient temperature of the three cities and gas consumption was generally associated with water heating and cooking. Gas consumption in Medellin is also lower because it has the lowest supply and connections for natural gas. In the UMPE report, the subsector with the highest electricity consumption for the three cities together is large establishments, with an average of 51.9 kilowatt hours per month per square meter. The subsector with the highest natural gas consumption is shopping centers, with an average of 9.3 cubic meters per month per square meter. High levels of gas usage are associated with cooking at food courts.

Table 1: 2007 Energy Consumption Indexes (Bottom-up Approach)[1]

Hotels	**Electricity (kWh/month/m^2)**		
	Bogotá	Medellín	Barranquilla
	7.85	6.87	13.88
	Natural Gas (m^3/month/m^2)		
	Bogotá	Medellín	Barranquilla
	0.91	0.33	0.35
Hospitals	**Electricity (kWh/month/m^2)**		
	Bogotá	Medellín	Barranquilla
	6.63	9.83	17.85
	Natural Gas (m^3/month/m^2)		
	Bogotá	Medellín	Barranquilla
	1.44	N/A	0.42
Businesses in SC	**Electricity (kWh/month/m^2)**		
	Bogotá	Medellín	Barranquilla
	28.84	41.50	72.11
	Natural Gas (m^3/month/m^2)		
	Bogotá	Medellín	Barranquilla
	17.00	2.02	8.93
Shopping Centers	**Electricity (kWh/month/m^2)**		
	Bogotá	Medellín	Barranquilla
	11.38	3.97	12.89
Large Establishments	**Electricity (kWh/month/m^2)**		
	Bogotá	Medellín	Barranquilla
	34.63	52.70	68.34
Offices	**Electricity (kWh/month/m^2)**		
	Bogotá	Medellín	Barranquilla

[1] The bottom up approach is based on the use of annual energy bills and direct measurements of specific projects that are then integrated to represent the sector as a whole.

	6.06	16.88	27.45

Source: (UPME 2007)

4.1.2 Bottom-up Approach: Estimating Base-Year Consumption Using Primary Data

Nineteen commercial building models were selected as prototypes for the simulation, based on whether they were representative of their category and whether survey data for was available to simulate energy usage. The surveys addressed technical and technological characteristics, architecture, and activities at the facilities. The energy simulations were performed in eQuest.[2]

The following types of buildings were included in the simulation:

Offices

- Typical corporate buildings with large surfaces divided into workstations ("open offices").
- Buildings with independent offices separated by walls, with minimal common areas. Office building less than 20 years old that are classified as Type A and B offices per e Colliers International classification system. Class A buildings are a maximum of 25 years old, with an area of at least 400 sqm and a height between floors and ceilings of at least 2.5 m. Class B buildings are a maximum of 40 years old, with an area of at least 150 sqm and a height between floors and ceilings of at least 2.3 m. These 20 year old or less buildings analyzed may or may not have ventilation systems and air conditioning. Air-conditioned buildings had centralized cooling towers and private air condition in each independent office. Most of the buildings surveyed had advanced communication, security, and fire devices.

Hospitals

- Level 1 hospitals are low-complexity centers that do not offer surgical services but provide outpatient services, an emergency room, and maternity wards. Level 1 hospitals comprised approximately 50 percent of the Health Services Institutions (IPS) in the three cities.
- Level 2 and 3 hospitals were excluded as there were too few facilities for comparison across the three cities (Appendix 1). (
- Level 4 hospitals, highly complex centers with intensive care wards, emergency rooms, laboratories, operating rooms, diagnostic facilities, and specialized outpatient services were included.

Hotels

- Four- and five-star hotels with over 150 rooms and ventilation systems and air conditioning. These hotels constituted the largest proportion of hotel space in the country. Appendix 1, contains a detailed analysis of hotel sector, including ratings, distribution, architectural characteristics

Shopping Centers

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[2] eQuest is a widely used, time-proven whole building energy performance design tool. This freeware tool was designed by Energy Design Resources and is available here: http://energydesignresources.com/resources/software-tools/equest.aspx .

- Large shopping centers (10,000–50,000 square meters) accounted for almost 35 percent of the total shopping center area in the country. Most had department stores, large-surfaces stores, single-product stores above 100 square meters, food courts, and movie theaters.

Appendix II provides a brief summary that includes all relevant information for each prototype used in the energy simulation. Table 2 summarizes the prototypes.

Table 2: Prototype Characteristics

Prototype Number	City	Use	Area (m^2)	Electricity Consumption (kWh/year)	Gas Consumption (m^3/year)
1	Bogotá	Shopping Mall	23,926	2,734.4	117,491.9
2	Medellín	Shopping Mall	54,112	5,355.7	28,452.8
3	Barranquilla	Shopping Mall	23,926	4,791.5	61,740.8
4	Bogotá	Office	53,130	6,585.8	0.0
5	Medellín	Office	25,101	4,890.0	0.0
6	Barranquilla	Office	12,136	4,280.3	0.0
7	Bogotá	Hospital	1,448	63.8	2,216.8
8	Medellín	Hospital	23,981	2,589.6	36,708.0
9	Barranquilla	Hospital	23,981	3,220.3	36,708.0
10	Bogotá	Hotel	21,890	2,081.4	30,535.1
11	Medellín	Hotel	12,706	1,088.7	17,724.0
12	Barranquilla	Hotel	7,940	1,409.2	52,445.0
13	Bogotá	Office	23,085	1,996.3	0.0
14	Bogotá	Office	23,085	2,417.0	0.0
15	Bogotá	Shopping Mall	12,626	4,053.6	25,757.0
16	Medellín	Shopping Mall	12,626	4,513.5	3,065.6
17	Barranquilla	Shopping Mall	12,626	5,212.5	9,505.1
18	Bogotá	Office	12,136	2,851.9	0.0
19	Bogotá	Hospital	24,534	6,222.7	35,184.7

4.1.3 Top-down Approach: Estimating Base-Year Consumption Using Consolidated Data

Using the BEN report and calculating the distribution of energy consumed in each major city, UDLA was able to estimate the total energy consumed by city. With this information, combined with distribution in the city property register, the team estimated the energy consumed by hotels, hospitals, shopping centers, and offices. The limitation of this method is that it assumes that all sectors have similar energy intensity, which is not always the case. Consequently, the team only used this method to validate the bottom-up estimates and verify orders of magnitude. This top-down estimation was carried out using the Long-Range Energy Alternatives Planning (LEAP) model (explained in Appendix III).

Table 3 presents the UDLA estimates of the electricity and natural gas consumption for 2012, disaggregated by sector and city.

Table 3: Energy Consumption Indexes (Top-down Approach)

Commercial Category	Electric Energy Consumption (kWh/year)	Constructed Area 2010 (m^2)	Consumption (kWh/month/m^2)
Bogotá			
Hospitals	337,910,820	1,076,837	26.15
Offices	570,644,100	15,418,715	3.08
Hotels	199,165,980	1,186,112	13.99
Shopping Centers	187,976,880	1,282,602	12.21
Medellín			
Hospitals	425,415,320	1,157,642	30.62
Offices	227,224,800	4,176,165	4.53
Hotels	142,646,680	951,525	12.49
Shopping Centers	49,232,040	1,203,647	3.41
Barranquilla			
Hospitals	142,600,776	214,598	55.38
Offices	22,240,488	422,885	4.38
Hotels	68,901,904	265,092	21.66
Shopping Centers	16,571,344	121,630	11.35

Data sources: SUI (2010), UPME (2010), property register office data, AILEG data.

4.1.4 Conclusion about Base-Year Consumption Estimation

Limited data are included in the BEN report (which does not segregate energy consumption by city) and the SUI (2010), which shows the total number of users, but does not classify them by sector. Also, access to SUI information has been restricted over the last two years. As a result, these data were not used to calculate energy consumption in the 2010 base year.

There were important differences between the results obtained through the bottom-up approach with existing data and the actual energy consumption information (utility bills). In particular, the bottom-up approach found higher consumption in shopping centers and office buildings. Significant energy efficiency efforts had already been implemented between the preparation of the UMPE 2007 and this study due to the high costs of energy over the last five years (Appendix I). In contrast to some of the projects surveyed in the 2007 UPME study, most of the current buildings had a centralized cooling system that increased energy demands. For the above reasons, the UDLA team used the bottom-up approach with primary data from surveyed prototypes to estimate baseline energy consumption per subsector and city.

4.2 COMMERCIAL SECTOR FORECASTS AND GREENHOUSE GAS SCENARIOS

4.2.1 Building Sector Growth Projections

The next step in generating the GHG emissions baselines was to forecast growth in the commercial building sector through 2040. The growth projections relied on the forecast exercises developed for the

ECDBC. This approach was adopted by the ECDBC to align the construction sector estimates with other economic sectors (e.g., agriculture, industry, and transport).

The main variable for commercial buildings was floor area. The UDLA team used the following steps to estimate growth projections:

1. Apply growth projections from 2010 through 2040 for indicators such as gross domestic product (GDP), GDP per capita, and construction sector GDP (Table 4). This was done in a manner consistent with macroeconomic forecasts developed by the ECDBC.

Table 4: Estimation of Growth Projections (2010–2040)

Indicator	2010–2015	2015–2020	2020–2025	2025–2030	2030–2035	2035–2040
GDP growth projections	4.22%	4.17%	4.05%	3.98%	3.90%	3.72%
GDP per capita growth projections	3.1%	3.1%	3.1%	3.1%	3.1%	3.1%
Construction sector GDP growth projections	4.40%	4.78%	5.12%	5.46%	5.35%	5.09%

Source: (DANE 2012)

2. Calculate the growth in total floor area (in square meters) for shopping centers, hospitals, hotels, and office buildings between 2010 and 2040, using the following information:
   a. GDP growth in the construction sector.
   b. The National Building Census developed by the National Department of Statistics (DANE). This census information was combined with GDP projections to obtain the total building floor area, using a time-series approach and the software Stata[3].
   c. Local cadastral data collected from the urban planning offices in the city councils of Bogotá, Medellín, and Barranquilla. The total building floor area per city was disaggregated by the four building categories (Table 5).

Table 5: Annual Estimated Floor Area per Subsector (2010–2040)

	Bogotá (1000 m^2)				Medellín (1000 m^2)				Barranquilla (1000 m^2)			
Year	Office Buildings	Shopping Centers	Hotels	Hospitals	Office Buildings	Shopping Centers	Hotels	Hospitals	Office Buildings	Shopping Centers	Hotels	Hospitals
2010	15,419,	1,283	1,186	1,077	4,176	1,204	951	1,158	423	121	265	215
2020	20,324	2,160	1,700	1,416	4,694	1,441	1,760	1,868	777	616	399	421
2030	29,365	3,896	2,541	2,146	6,643	2,128	3,044	3,076	1,351	1,684	718	814
2040	46,237	7,310	3,953	3,662	11,863	3,797	5,027	5,098	2,287	3,910	1,420	1,565

Data source: (DANE 2012)

[3] Stata statistical software is an integrated statistical software package that provides tools for data analysis, data management, and graphics: www.stata.com

In projecting the growth of floor area, the most significant data limitations were the following:

- Each of the three city councils used a different method to organize and classify cadastral data.
- Before 2006, data from the National Building Census were not disaggregated by category of building.

Consistent with ECDBC practices, two different scenarios were considered in estimating GHG emission baselines—a business-as-usual (BAU) scenario and a reference scenario.

4.2.2 Business-as-Usual Scenario

The BAU scenario reflected the GHG emissions baseline for each of the four building categories. It was based on the following information:

- The building stock projection and floor area growth rate per city and per building category from 2010 to 2040
- The base year consumption information derived from the bottom-up approach
- The baseline emission factor for electricity consumption was 48.61 Gigagrams of carbon dioxide per Petajoule ($GgCO_2$/PJ)
- The baseline emission factor for natural gas consumption was 60.23 $GgCO_2$/PJ (0.037455 Gigajoules per cubic meter) for Bogotá, ands 55.34 $GgCO_2$/PJ (0.043795 (GJ/m^3) for Medellín and Baranquilla. [4]
- The prices of electricity and natural gas in the commercial sector, which were assumed to be constant over the study period (Appendix V)

There was one emission baseline for each building category and each city. The GHG emission baselines for 2010 to 2040 were generated by multiplying the emission factor by the annual consumption estimate (the product of the annual built floor area and the energy consumption index for the subsector).

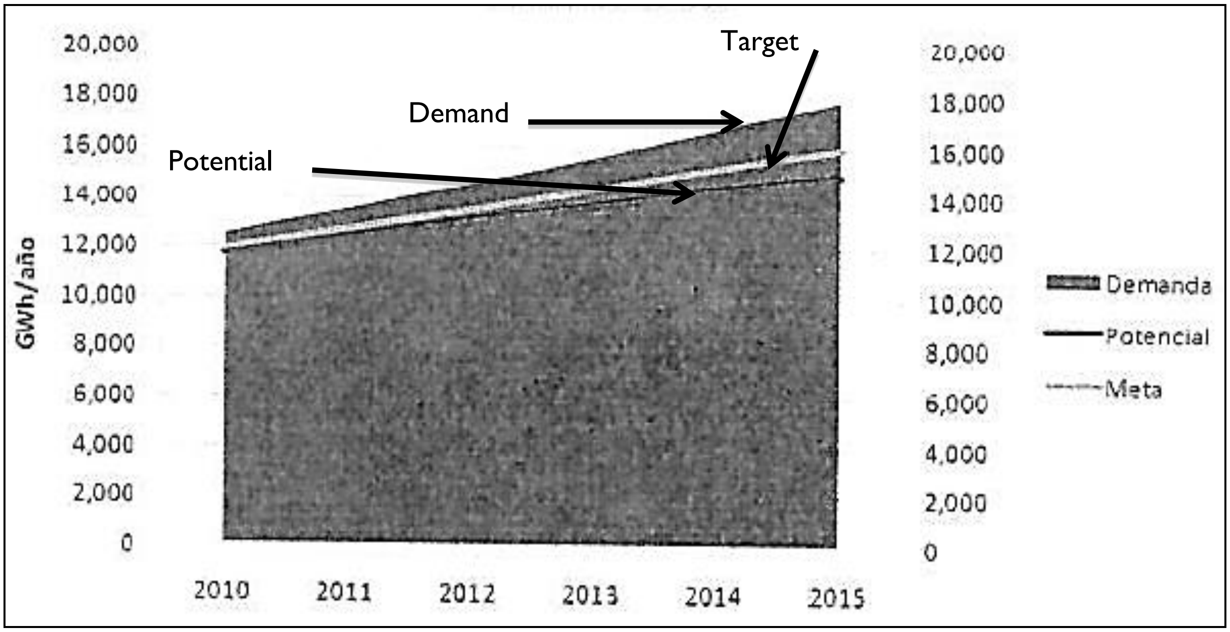
4.2.3 Reference Scenario

The reference scenario reflected changes in public policies aimed at increasing energy efficiency, including changes that have been established but not yet implemented. The reference scenario also included macroeconomic, social and market variables from the Rational and Efficient Use of Energy and Unconventional Sources Program (PROURE) of the Ministry of Mining and Energy and UPME.

The energy efficiency program included energy savings targets for 2015, which were based on estimates from UPME that considered macroeconomic, social, and market variables (UPME and Ministry of Mining and Energy 2010). Figure 4 shows PROURE's commercial energy savings targets for 2010 to 2015; there were no studies for additional periods., An energy savings target of 10 percent was expected for commercial buildings for 2015 (UPME and Ministry of Mining and Energy 2010).

[4] Appendix IV discusses the calculation of the emission factors.

Figure 4: Commercial Sector Demand, Potential, and Savings Targets



Source: UPME and Ministry of Mining and Energy (2010)

In developing the reference curves, the UDLA team assumed a constant energy-saving target of 10 percent every five years through 2040. Since PROURE only addressed savings on electricity, it was not possible to calculate the reference curves for natural gas (Appendix VI)

4.2.4 Business-as-Usual Scenario versus Reference Scenario

Appendix VII presents the BAU and reference curves. As expected, the BAU approach showed higher GHG emissions than the reference scenario. The mitigation potential of the proposed measures was calculated using the BAU scenario since PROURE did not set targets for the entire period of this study. Although the reference scenario was not used to calculate the MACCs, it is presented for comparative purposes and discussed in the conclusions.

4.3 GREENHOUSE GAS EMISSION MITIGATION MEASURES

4.3.1 Identifying Mitigation Options

The study included the following types of mitigation measures:

- Architectural and materials isolation options for new buildings and retrofits
- Lighting technologies
- HVAC technologies
- Improvements in energy building infrastructure
- Cooling and cooking options

Appendix VIII summarizes the feasible mitigation measures identified by surveying actual building projects.

4.3.2 Selecting and Evaluating Mitigation Potential

All prototypes were examined using an energy simulation tool (eQuest). The input data included technical and architectural features as well as current energy consumption. The eQuest software allowed the UDLA team to incorporate local conditions (such as lighting and temperature) and analyze operational aspects (e.g., consumption patterns in every space). The team also looked at the interaction of loads from lighting, equipment and people with air conditioning and heating. This approach allowed close to 30 mitigation measures to be considered for each prototype. Appendix IX contains more detailed information on energy modeling in eQuest.

The 16 GHG mitigation measures described in Appendix X were applied for each prototype. The team evaluated most measures in eQuest to estimate energy and cost savings, initially applying the measures independently and then combining them to account for duplication and mutually exclusive alternatives.

1.1.1.1 *Adoption Rates for Mitigation Measures*

Adoption of GHG mitigation measures in the building sector depends on the following factors:

- Cost-benefit analysis of the technologies
- Availability of local knowledge and resources to support implementation and operation throughout the buildings' life cycles
- Capacity of the sector to introduce new technologies for construction and operation
- Knowledge and commitment of the tenants and property managers about energy efficiency
- Government incentives to implement the GHG mitigation measures

The UDLA team assumed that:

- Each building would apply the measure only once during the study period
- The useful life of a building was 40 years
- The demolition of buildings in the sector would be minimal and could be omitted

The team considered three time horizons for the implementation of the measures -- short-term (2010–2018), medium-term (2019–2025), and long-term (2025–2040).

Annual adoption rates were determined for new and existing buildings by taking into account the observations in the characterization report. Table 6 summarizes these adoption rates and an estimate of the new building stock during the period of study. It shows the relative importance of new buildings over existing ones and the impact of promoting GHG mitigation actions.

Table 6: Percentage of Building Stock Applying Mitigation Measures Annually

City	Existing Buildings			New Buildings			Buildings Built During the Study Period Since 2010
	Short-Term	Medium-Term	Long-Term	Short-Term	Medium-Term	Long-Term	
Bogotá	20%	30%	40%	50%	70%	100%	82%
Medellín	20%	30%	40%	50%	70%	100%	68%
Baranquilla	20%	30%	40%	50%	70%	100%	97%

To date, retrofit processes have not been widely considered by commercial buildings in Colombia, because of the investment and logistical requirements. However, stakeholders in new projects are demanding sustainability features, including energy efficiency.

1.1.1.2 *Groups of Mitigation Measures*

Table 7 shows groups of energy efficiency measures. The UDLA team created the groups to avoid overlaps.

Table 7: Groups of Measures Created to Avoid Overlap

Group	Energy Efficiency Measures
1	Orientation of the building floor
2	Façade insulation (R–12)[5] Single-layer low-emissivity glass Sunbreaks and eaves Double-tinted glass Double-layer low-emissivity glass Roof insulation (R–20)
3	Lighting efficiency
4	Light dimming
5	Automated lighting
6	Infrastructure improvements
7	Efficient refrigerators
8	Automation of air conditioning
9	Efficient HVAC systems HVAC economizers[6]
10	Efficient stoves

Only the most efficient measure from each group was selected and included in the MACCs. Some mitigation measures were excluded due to their high costs and low potential, which is why the various MACCs do not all include the same number of measures.

[5] The R-value is a measure of thermal resistance used in the building and construction industry. Under uniform conditions, it is the ratio of the temperature difference across an insulator and the heat flux through it (heat transfer per unit area per unit time, $\dot{Q}_A$) $R = \Delta T / \dot{Q}_A$. The R-12 polystyrene insulation is the measure analyzed here. See Appendix X and Appendix X1 for details on the efficiency measures.

[6] An energy efficiency device for AC equipment that recycles fresh air from outside the building. Appropriate in Bogotá, where day temperatures are between 8^C and 20^C (Appendix X).

4.3.3 Estimating Costs of Measures Implementation

Appendix XI summarizes the details taken into account in calculating the implementation costs incurred in applying the GHG mitigation measures. A separate calculation was developed for new and existing buildings (retrofits).Cost calculations addressed both additive and replacement measures.

Additive measures install additional features without removing anything. Examples include facades and roof isolation, sunbreaks, lighting and HVAC automation devices, and light dimmers. The cost of these measures is the same for new and existing buildings.

Replacement measures include new window glass, light bulbs, refrigerators, and stoves. The costs of these measures differ for new and existing buildings. For existing buildings, the cost is the full price of the new technology. The study assumed that existing buildings would lose the salvage value of old technologies. New buildings should only consider using the newer and most efficient technologies. The capital requirement for replacement measures in new buildings is the difference in cost between the low-carbon technologies and the least-cost conventional alternatives.

Table 8: Capital and Operating Costs for Implementing Mitigation Measures

	Additive Measures	Replacement Measures
Existing Buildings	• Capital requirements: the full cost of the mitigation technology • Operating costs: savings associated with the mitigation measure	• Capital requirements: the full cost of the mitigation technology (no salvage value) • Operating costs: savings associated with the mitigation measure
New Buildings	• Capital requirements: the full cost of the mitigation technology • Operating costs: savings associated with the mitigation measure	• Capital requirements: the difference in cost between the least-cost conventional technology and the mitigation option • Operating costs: savings associated with the mitigation measure

The UDLA team made the following assumptions in calculating costs for replacement measures:

- **Lighting efficiency.** Information from local suppliers was used to assess the cost of replacing conventional lighting with LEDs. For each building prototype, it was assumed that the entire building would switch to LEDs.
- **HVAC premium.** Replacement costs were calculated per square meter, based on a case study on installation of new equipment. Both the percentage reduction in electricity consumption and the cost associated with upgrading the equipment were considered.
- **Efficient cooling.** This measure took into account variations in the cost of refrigeration equipment. The market prices of both conventional and high-efficiency equipment were used to calculate the cost of replacing existing equipment in old buildings. They were also employed to estimate the cost of purchasing high-efficiency equipment for new buildings.
- **Efficient cooking.** The difference in cost between traditional cooking options and low-carbon technologies was approximately 40 percent of the cost of energy-efficient stoves.

Table 9 summarizes the mitigation options evaluated for each prototype.

Table 9: Mitigation Options Considered

Measures		Bogotá				Medellín				Baranquilla			
		Shopping	Offices	Hospitals	Hotels	Shopping Centers	Offices	Hospitals	Hotels	Shopping Centers	Offices	Hospitals	Hotels
1	Roof insulation	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
2	Facade insulation	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
3	Single-layer glass	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
4	Double-layer glass	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
5	Tinted double-layer glass	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
6	Sunbreaks	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
7	Building orientation	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
8	Lighting efficiency	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
9	Light dimming	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
10	Lighting automation	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
11	HVAC premium	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
12	HVAC energy savers	Y	Y	N	N	N	N	N	N	N	N	N	N
13	AC occupancy	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y
14	Infrastructure improvements	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
15	Efficient cooling	Y	N	Y	Y	Y	N	Y	Y	Y	N	Y	Y
16	Efficient cooking	Y	N	Y	Y	Y	N	Y	Y	Y	N	Y	Y

Legend: Y = Yes; N = No.

ESTIMATION OF MARGINAL MITIGATION COSTS

The UDLA team used the following procedure to develop the MACCs:

1. Evaluate every measure for new and existing buildings for each city and subsector, including:
    a. Incremental capital requirements for the mitigation options, including technology and labor costs
    b. Changes in operating costs/savings
    c. Adoption rate per year for new and existing buildings

2. Calculate the CO_2 mitigation potential by multiplying:
    a. Energy savings (kWh/year/m^2)
    b. Area of the building stock that could implement the measure per year (m^2)
    c. Adoption rate (percentage)
    d. Emission factor (metric tons of CO_2/kWh for electricity or tons of CO_2/m^3 for gas)

3. Estimate the NPV for each measure for all costs, including capital and operating, at a 10 percent real discount rate.[7] The NPV took into account the operating and capital costs savings between the conventional and mitigation options.)

4. Calculate the cost per ton of CO_2 reduced from the implementation of each measure by dividing the NPV by the mitigation potential.

5. Group measures to account for interactions and overlaps.

6. Formulate two sets of MACCs --1) total technology (materials) and labor costs for each measure, and 2) only technology costs. Both MAC curves were estimated with the same operating costs and CO_2 reduction assumptions.

Appendix XII contains more details on the method used to calculate the mitigation potential and the costs and benefits.

[7] A 10% discount rate is consistent with those used in the suite of MAC Curve analyses for other sectors prepared for MADS in Colombia. Note that USAID analyses typically use a 12% discount rate.

5. RESULTS

The following options had the lowest implementation costs:

- Shopping centers
  - Lighting automation for new and existing buildings in the three cities
  - HVAC automation in Medellín and Barranquilla

- Office buildings
  - HVAC automation in Barranquilla
  - Lighting dimming and automation in Bogotá
  - Facade isolation in Bogotá

- Hospitals
  - HVAC automation in Bogotá and Medellín
  - Lighting automation in the three cities
  - Efficient stoves in the three cities

- Hotels
  - HVAC automation in Barranquilla
  - Lighting automation in Bogotá and Barranquilla
  - Efficient stoves in the three cities

In most cases, changing the orientation of the building had an interesting mitigation potential and zero cost. Although this conclusion was based on surveyed prototypes, it indicates the importance of considering bioclimatic principles in building design.

Some mitigation measures (LED lighting, light dimmers, and replacement of refrigerators and stoves)—did not have substantial potential due to the high technology costs in Colombia. Although operational savings were considerable for these measures, the savings did not compensate for higher capital requirements.

Bogotá had considerable mitigation potential, mainly from use of more-efficient lighting technology. In the milder climate of Medellín and the hotter climate of Barranquilla, there were important mitigation opportunities from upgrading or automating HVAC systems. Reducing energy consumption from lighting also showed good potential in these cities.

If all analyzed measures were implemented during the study period, regardless of cost, Bogotá would have a mitigation potential of 1.9 million tons of CO_2e, 91 percent from office building lighting. Medellín's mitigation potential would be 151,000 tons of CO_2e and Barranquilla's would be 120,000 tons of CO_2e. Offices accounted for the largest share of potential mitigation in Medellín and Barranquilla; hotels and hospitals accounted for the smallest share. The differences in the three cities' total mitigation potential largely reflected their socio-economic importance and population.

Figure 5: MAC Curve for Shopping Centers (Including Total Implementation Costs)

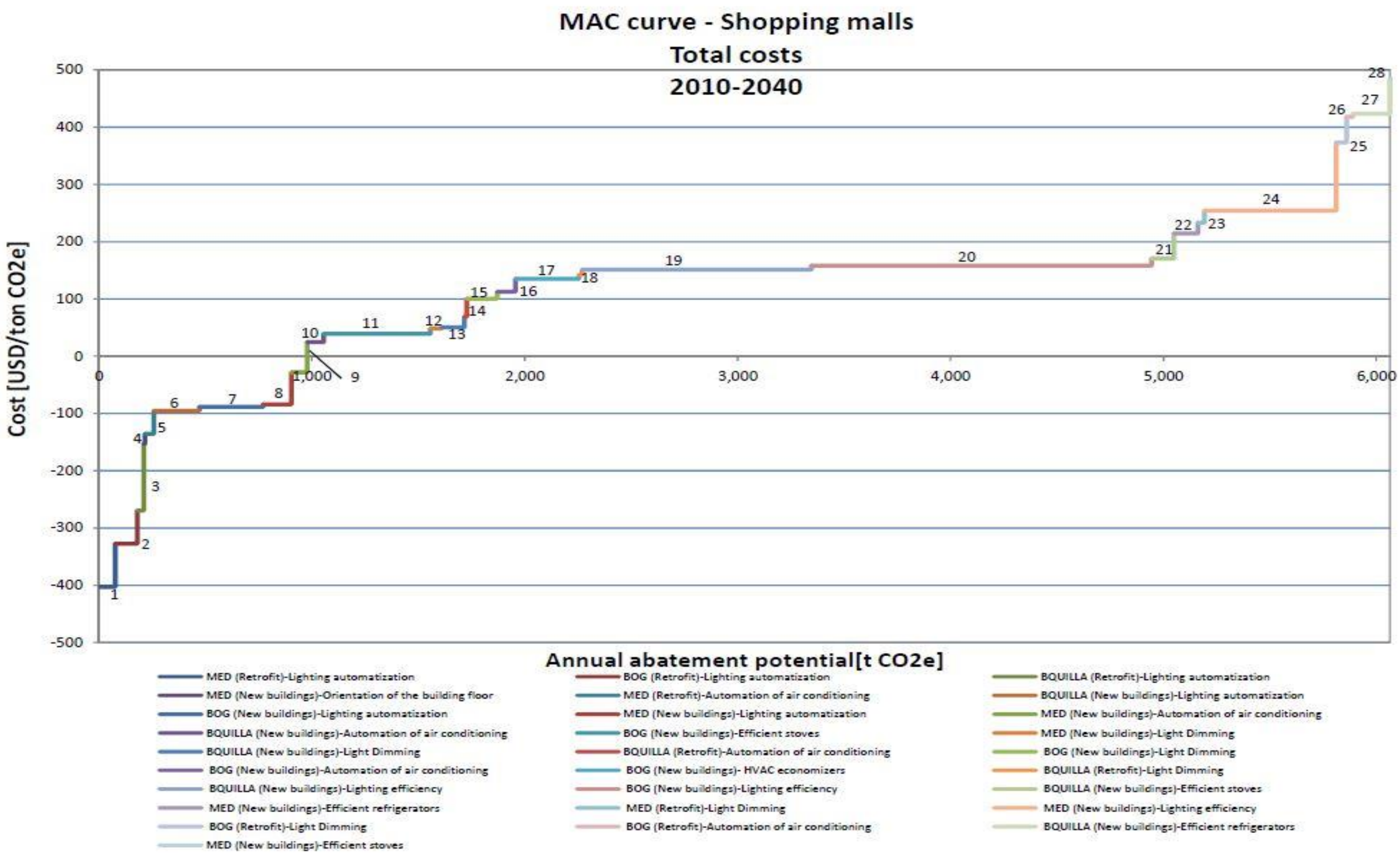


Table 10: MACC Input Information for Shopping Centers (Including Total Implementation Costs)

No.	Mitigation Measure	Annual Potential (Tons CO_2e)	Cost ($/ton CO_2e)
1	Medellín (Retrofit) Automated lighting	76.50	-402.92
2	Bogotá (Retrofit) Automated lighting	104.19	-327.37
3	Baranquilla (Retrofit) Automated lighting	29.50	-269.46
4	Medellín (New buildings) Orientation of the building floor	6.07	-152.81
5	Medellín (Retrofit) Automation of air conditioning	42.37	-135.63
6	Baranquilla (New buildings) Automated lighting	214.76	-95.34
7	Bogotá (New buildings) Automated lighting	298.38	-88.17
8	Medellín (New buildings) Automated lighting	132.98	-83.80
9	Medellín (New buildings) Automation of air conditioning	73.65	-28.21
10	Baranquilla (New buildings) Automation of air conditioning	77.81	24.46
11	Bogotá (New buildings) Efficient stoves	501.01	38.95
12	Medellín (New buildings) Light dimming	53.09	48.49
13	Baranquilla (New buildings) Light dimming	106.46	50.31
14	Baranquilla (Retrofit) Automation of air conditioning	10.69	69.12
15	Bogotá (New buildings) Light dimming	143.39	100.51
16	Bogotá (New buildings) Automation of air conditioning	85.33	112.62
17	Bogotá (New buildings) HVAC economizers	298.68	134.92
18	Baranquilla (Retrofit) Light dimming	14.62	142.18
19	Baranquilla (New buildings) Lighting efficiency	1,076.94	151.08
20	Bogotá (New buildings) Lighting efficiency	1,598.16	158.06
21	Baranquilla (New buildings) Efficient stoves	105.30	170.69
22	Medellín (New buildings) Efficient refrigerators	112.64	214.54
23	Medellín (Retrofit) Light dimming	30.54	233.15
24	Medellín (New buildings) Lighting efficiency	618.24	254.25
25	Bogotá (Retrofit) Light dimming	50.07	373.19
26	Bogotá (Retrofit) Automation of air conditioning	29.80	418.15
27	Baranquilla (New buildings) Efficient refrigerators	172.59	423.41
28	Medellín (New buildings) Efficient stoves	17.02	484.30

Figure 6: MAC Curve for Office Buildings (Including Total Implementation Costs)

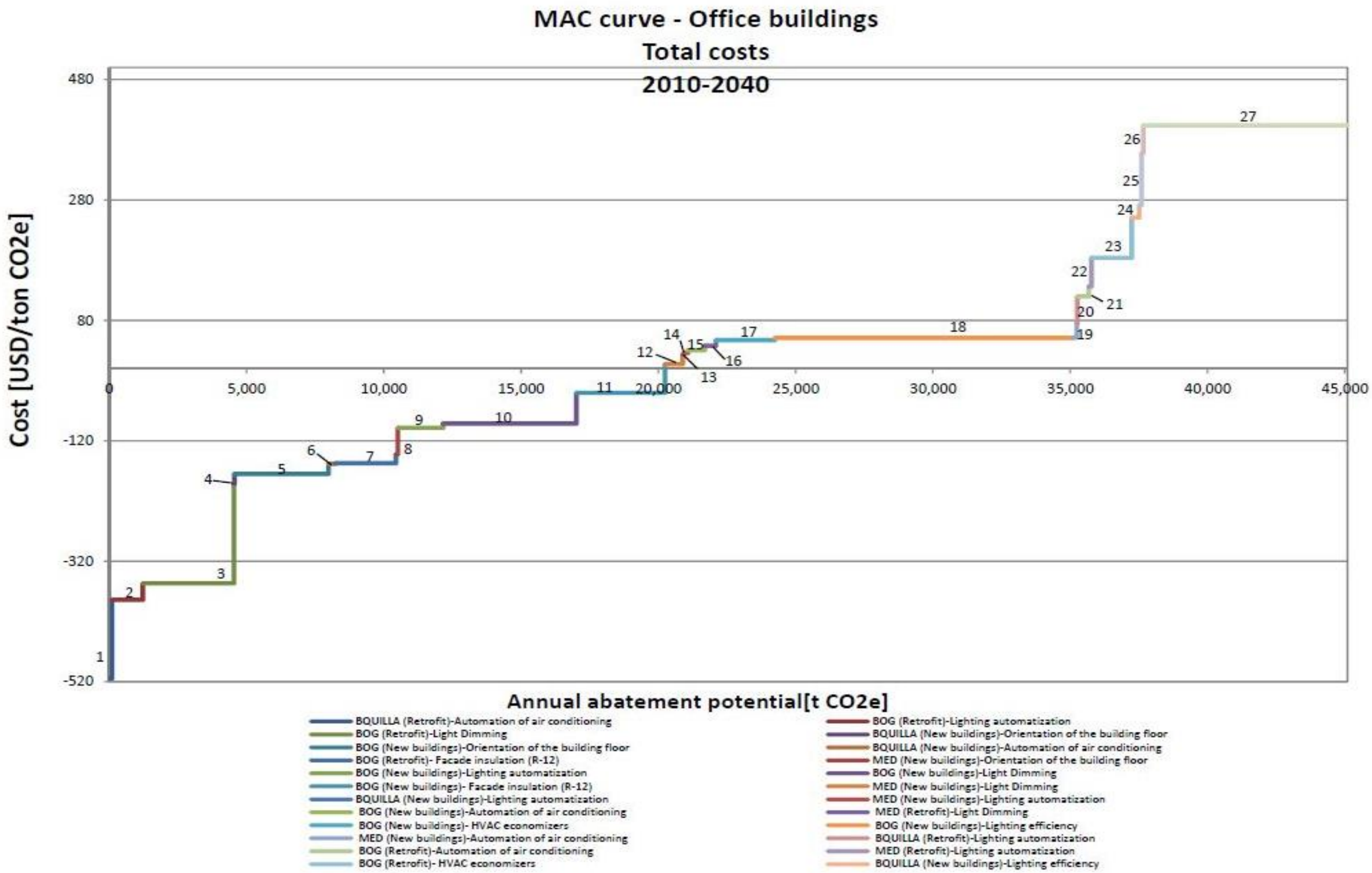


Table 11: MACC Input Information for Office Buildings (Including Total Implementation Costs)

No.	Mitigation Measure	Annual Potential (Tons CO_2e)	Cost ($/ton CO_2e)
1	Baranquilla (Retrofit) Automation of air conditioning	98.78	-514.41
2	Bogotá (Retrofit) Automated lighting	1,124.94	-384.11
3	Bogotá (Retrofit) Light dimming	3,316.97	-356.54
4	Baranquilla (New buildings) Orientation of the building floor	18.96	-191.35
5	Bogotá (New buildings) Orientation of the building floor	3,431.72	-174.87
6	Baranquilla (New buildings) Automation of air conditioning	244.23	-158.19
7	Bogotá (Retrofit) Facade insulation (R-12)	2,207.13	-157.16
8	Medellín (New buildings) Orientation of the building floor	69.27	-142.19
9	Bogotá (New buildings) Automated lighting	1,646.21	-98.29
10	Bogotá (New buildings) Light dimming	4,853.96	-91.24
11	Bogotá (New buildings) Facade insulation (R-12)	3,229.86	-40.22
12	Medellín (New buildings) Light dimming	643.77	7.20
13	Baranquilla (New buildings) Automated lighting	37.73	23.29
14	Medellín (New buildings) Automated lighting	152.69	25.92
15	Bogotá (New buildings) Automation of air conditioning	613.34	30.67
16	Medellín (Retrofit) Light dimming	409.45	37.99
17	Bogotá (New buildings) HVAC economizers	2,145.93	47.07
18	Bogotá (New buildings) Lighting efficiency	10,866.94	50.85
19	Medellín (New buildings) Automation of air conditioning	132.52	51.51
20	Baranquilla (Retrofit) Automated lighting	15.26	75.74
21	Bogotá (Retrofit) Automation of air conditioning	419.13	119.87
22	Medellín (Retrofit) Automated lighting	97.12	136.73
23	Bogotá (Retrofit) HVAC economizers	1,466.43	183.93
24	Baranquilla (New buildings) Lighting efficiency	273.65	250.98
25	Medellín (Retrofit) Automation of air conditioning	84.29	271.69
26	Baranquilla (New buildings) Light dimming	66.85	357.96
27	Bogotá (Retrofit) Lighting efficiency	7,425.95	403.84

Figure 7: MAC Curve for Hospitals (Including Total Implementation Costs)

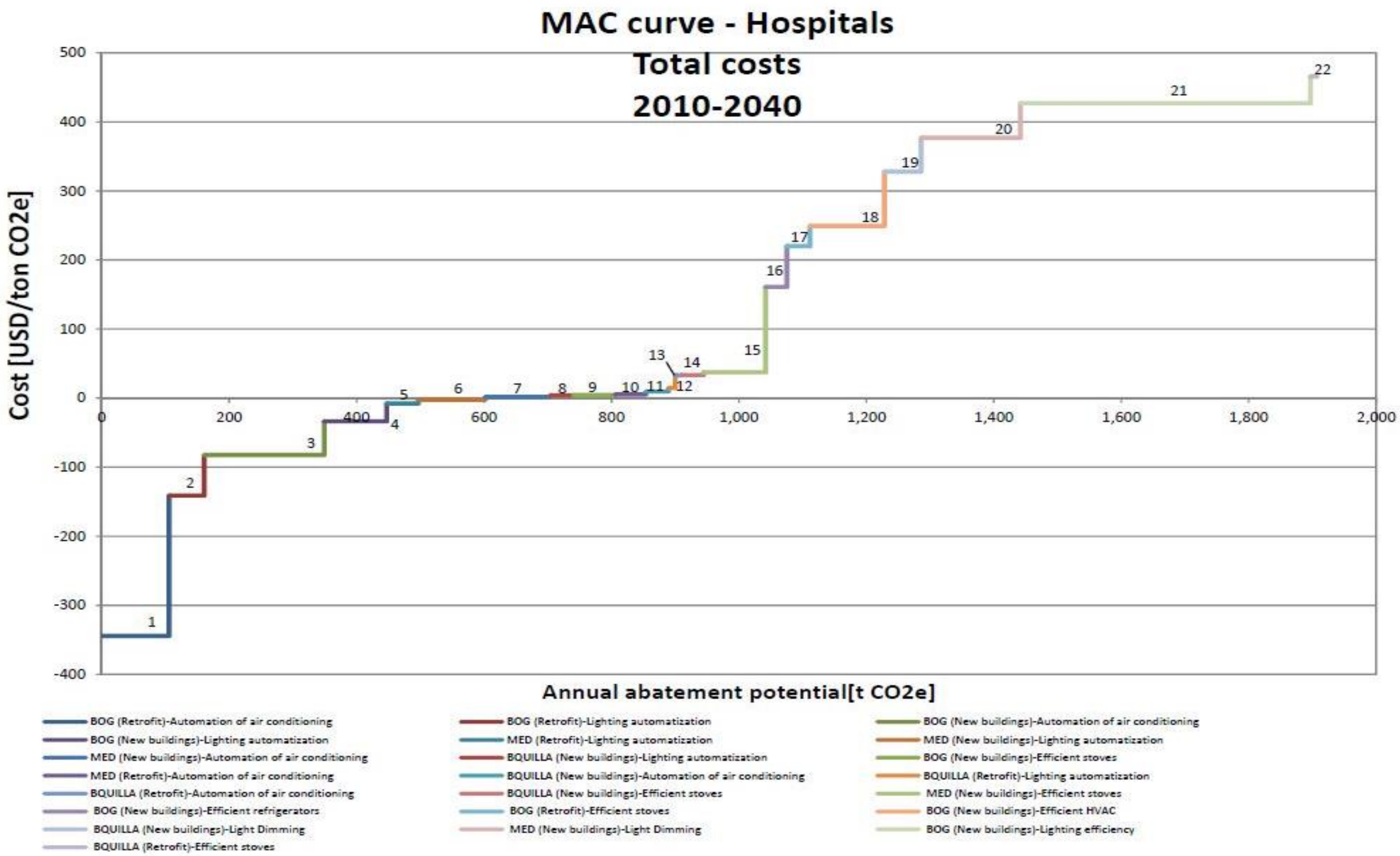


Table 12: MACC Input Information for Hospitals (Including Total Implementation Costs)

No.	Mitigation Measure	Annual Potential (Tons CO_2e)	Cost ($/ton CO_2e)
1	Bogotá (Retrofit) Automation of air conditioning	105.72	-344.36
2	Bogotá (Retrofit) Automated lighting	55.21	-140.83
3	Bogotá (New buildings) Automation of air conditioning	188.21	-82.19
4	Bogotá (New buildings) Automated lighting	98.28	-33.61
5	Medellín (Retrofit) Automated lighting	49.55	-7.81
6	Medellín (New buildings) Automated lighting	104.91	-2.26
7	Medellín (New buildings) Automation of air conditioning	102.46	1.57
8	Baranquilla (New buildings) Automated lighting	36.62	4.20
9	Bogotá (New buildings) Efficient stoves	64.69	4.38
10	Medellín (Retrofit) Automation of air conditioning	48.39	5.44
11	Baranquilla (New buildings) Automation of air conditioning	35.35	9.57
12	Baranquilla (Retrofit) Automated lighting	10.81	14.58
13	Baranquilla (Retrofit) Automation of air conditioning	10.43	33.23
14	Baranquilla (New buildings) Efficient stoves	33.98	33.43
15	Medellín (New buildings) Efficient stoves	97.41	37.33
16	Bogotá (New buildings) Efficient refrigerator	33.30	160.95
17	Bogotá (Retrofit) Efficient stoves	36.34	220.05
18	Bogotá (New buildings) Efficient HVAC	116.65	249.34
19	Baranquilla (New buildings) Light dimming	57.66	328.00
20	Medellín (New buildings) Light dimming	155.85	376.87
21	Bogotá (New buildings) Lighting efficiency	455.27	427.07
22	Baranquilla (Retrofit) Efficient stoves	10.03	465.81

Figure 8: MAC Curve for Hotels (Including Total Implementation Costs)

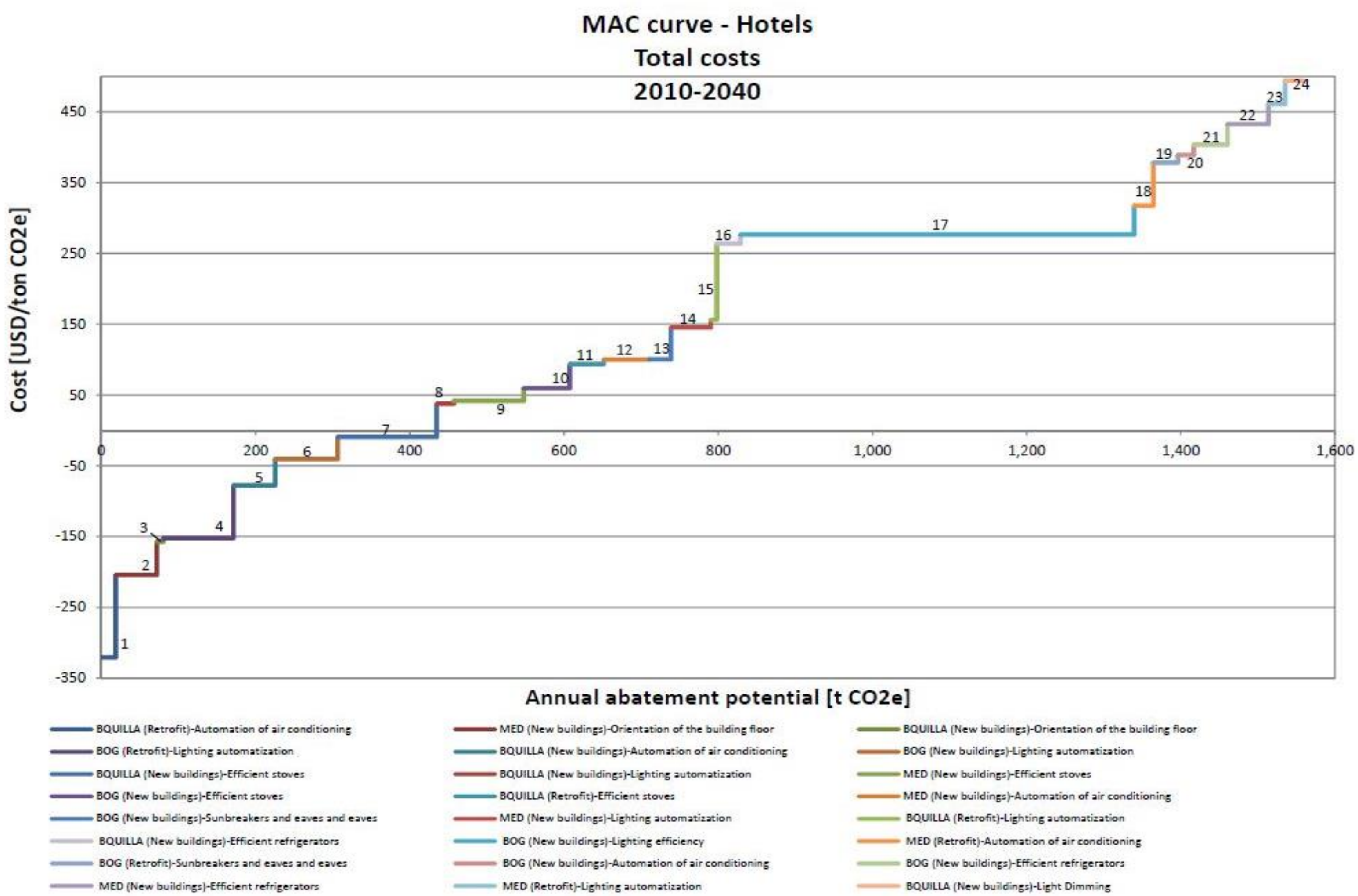


Table 13: MACC Input Information for Hotels (Including Total Implementation Costs)

No.	Mitigation Measure	Annual Potential (Tons CO_2e)	Cost ($/ton CO_2e)
1	Baranquilla (Retrofit) HVAC automation	18.60	-320.57
2	Medellín (New buildings) Orientation of the building floor	53.27	-204.34
3	Baranquilla (New buildings) Orientation of the building floor	8.43	-157.28
4	Bogotá (Retrofit) Automated lighting	90.90	-152.29
5	Baranquilla (New buildings) HVAC automation	54.21	-77.54
6	Bogotá (New buildings) Automated lighting	81.18	-40.47
7	Baranquilla (New buildings) Efficient stoves	128.33	-9.24
8	Baranquilla (New buildings) Automated lighting	22.16	37.81
9	Medellín (New buildings) Efficient stoves	90.73	41.79
10	Bogotá (New buildings) Efficient stoves	59.60	59.64
11	Baranquilla (Retrofit) Efficient stoves	44.04	93.74
12	Medellín (New buildings) HVAC automation	59.16	100.02
13	Bogotá (New buildings) Sunbreaks and eaves	28.40	100.53
14	Medellín (New buildings) Automated lighting	51.50	145.27
15	Baranquilla (Retrofit) Automated lighting	7.60	156.34
16	Baranquilla (New buildings) Refrigeration efficiency	30.79	264.01
17	Bogotá (New buildings) Lighting efficiency	510.57	276.67
18	Medellín (Retrofit) HVAC automation	24.87	317.40
19	Bogotá (Retrofit) Sunbreaks and eaves	31.80	378.29
20	Bogotá (New buildings) HVAC automation	20.68	388.81
21	Bogotá (New buildings) Refrigeration efficiency	43.90	403.69
22	Medellín (New buildings) Refrigeration efficiency	53.02	432.54
23	Medellín (Retrofit) Automated lighting	21.65	460.99
24	Baranquilla (New buildings) Lighting dimming	23.13	493.87

Figure 9: MAC Curve for Shopping Centers (Including Only Technology Costs)

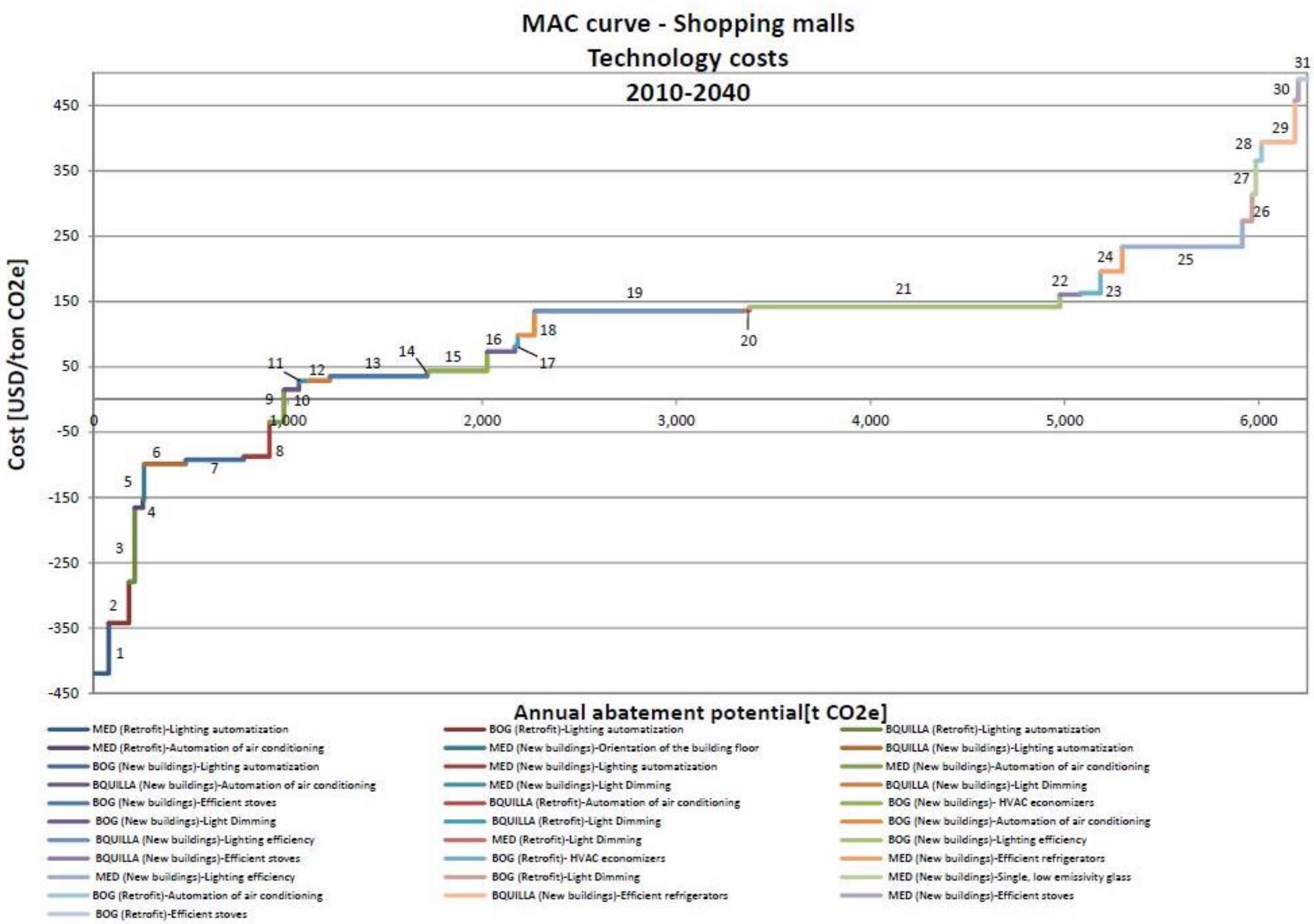


Table 14: MACC Input Information for Shopping Centers (Including Only Technology Costs)

No.	Mitigation Measure	Annual Potential (Tons CO_2e)	Cost ($/ton CO_2e)
1	Medellín (Retrofit) Automated lighting	76.50	-419.52
2	Bogotá (Retrofit) Automated lighting	104.19	-342.30
3	Baranquilla (Retrofit) Automated lighting	29.50	-279.08
4	Medellín (Retrofit) Automation of air conditioning	42.37	-165.59
5	Medellín (New buildings) Orientation of the building floor	6.07	-152.81
6	Baranquilla (New buildings) Automated lighting	214.76	-98.75
7	Bogotá (New buildings) Automated lighting	298.38	-92.19
8	Medellín (New buildings) Automated lighting	132.98	-87.25
9	Medellín (New buildings) Automation of air conditioning	73.65	-34.44
10	Baranquilla (New buildings) Automation of air conditioning	77.81	15.06
11	Medellín (New buildings) Light dimming	53.09	28.36
12	Baranquilla (New buildings) Light dimming	106.46	28.94
13	Bogotá (New buildings) Efficient stoves	501.01	35.57
14	Baranquilla (Retrofit) Automation of air conditioning	10.69	42.57
15	Bogotá (New buildings) HVAC economizers	298.68	43.87
16	Bogotá (New buildings) Light dimming	143.39	73.60
17	Baranquilla (Retrofit) Light dimming	14.62	81.78
18	Bogotá (New buildings) Automation of air conditioning	85.33	98.56
19	Baranquilla (New buildings) Lighting efficiency	1,076.94	135.36
20	Medellín (Retrofit) Light dimming	30.54	136.36
21	Bogotá (New buildings) Lighting efficiency	1,598.16	141.73
22	Baranquilla (New buildings) Efficient stoves	105.30	160.56
23	Bogotá (Retrofit) HVAC economizers	104.29	162.87
24	Medellín (New buildings) Efficient refrigerators	112.64	196.18
25	Medellín (New buildings) Lighting efficiency	618.24	233.90
26	Bogotá (Retrofit) Light dimming	50.07	273.27
27	Medellín (New buildings) Single, low-emissivity glass	18.82	314.18
28	Bogotá (Retrofit) Automation of air conditioning	29.80	365.94

No.	Mitigation Measure	Annual Potential (Tons CO_2e)	Cost ($/ton CO_2e)
29	Baranquilla (New buildings) Efficient refrigerators	172.59	394.07
30	Medellín (New buildings) Efficient stoves	17.02	458.72
31	Bogotá (Retrofit) Efficient stoves	174.95	490.56

Figure 10: MAC Curve for Office Buildings (Including Only Technology Costs)

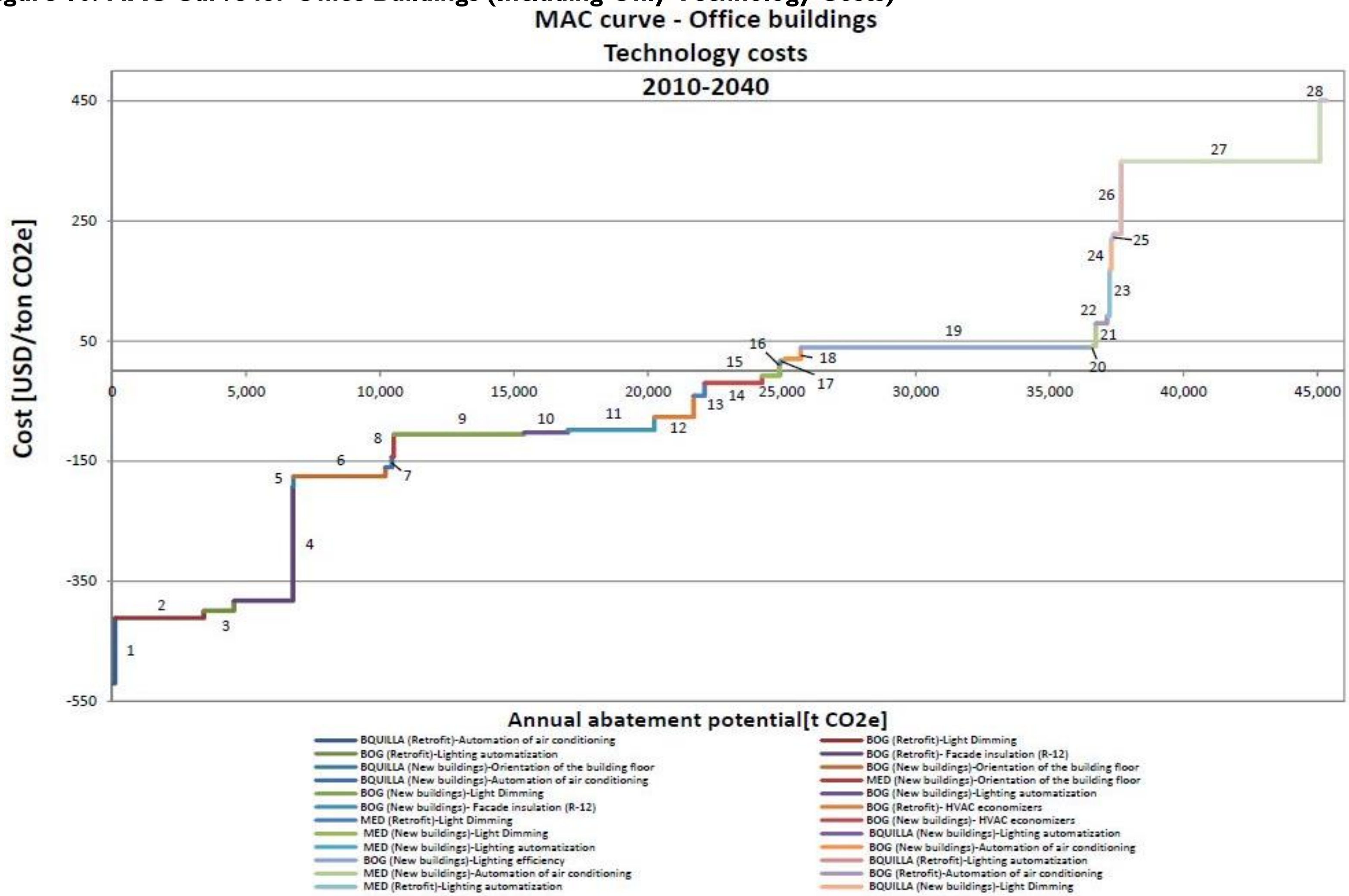


Table 15: MACC Input Information for Office Buildings (Including Only Technology Costs)

No.	Mitigation Measure	Annual Potential (Tons CO_2e)	Cost ($/ton CO_2e)
1	Baranquilla (Retrofit) Automation of air conditioning	98.78	-519.81
2	Bogotá (Retrofit) Light dimming	3,316.97	-411.19
3	Bogotá (Retrofit) Automated lighting	1,124.94	-399.08
4	Bogotá (Retrofit) Facade insulation (R-12)	2,207.13	-382.29
5	Baranquilla (New buildings) Orientation of the building floor	18.96	-191.35
6	Bogotá (New buildings) Orientation of the building floor	3,431.72	-174.87
7	Baranquilla (New buildings) Automation of air conditioning	244.23	-159.85
8	Medellín (New buildings) Orientation of the building floor	69.27	-142.19
9	Bogotá (New buildings) Light dimming	4,853.96	-105.22
10	Bogotá (New buildings) Automated lighting	1,646.21	-102.12
11	Bogotá (New buildings) Facade insulation (R-12)	3,229.86	-97.83
12	Bogotá (Retrofit) HVAC economizers	1,466.43	-76.26
13	Medellín (Retrofit) Light dimming	409.45	-40.80
14	Bogotá (New buildings) HVAC economizers	2,145.93	-19.52
15	Medellín (New buildings) Light dimming	643.77	-7.74
16	Baranquilla (New buildings) Automated lighting	37.73	12.56
17	Medellín (New buildings) Automated lighting	152.69	17.52
18	Bogotá (New buildings) Automation of air conditioning	613.34	20.40
19	Bogotá (New buildings) Lighting efficiency	10,866.94	39.56
20	Baranquilla (Retrofit) Automated lighting	15.26	40.84
21	Medellín (New buildings) Automation of air conditioning	132.52	41.82
22	Bogotá (Retrofit) Automation of air conditioning	419.13	79.71
23	Medellín (Retrofit) Automated lighting	97.12	92.39
24	Baranquilla (New buildings) Light dimming	66.85	169.85
25	Medellín (Retrofit) Automation of air conditioning	84.29	220.61
26	Baranquilla (New buildings) Lighting efficiency	273.65	228.86
27	Bogotá (Retrofit) Lighting efficiency	7,425.95	349.48
28	Baranquilla (New buildings) Electric Systems Improvements	242.56	450.89

Figure 11: MAC Curve for Hospitals (Including Only Technology Costs)

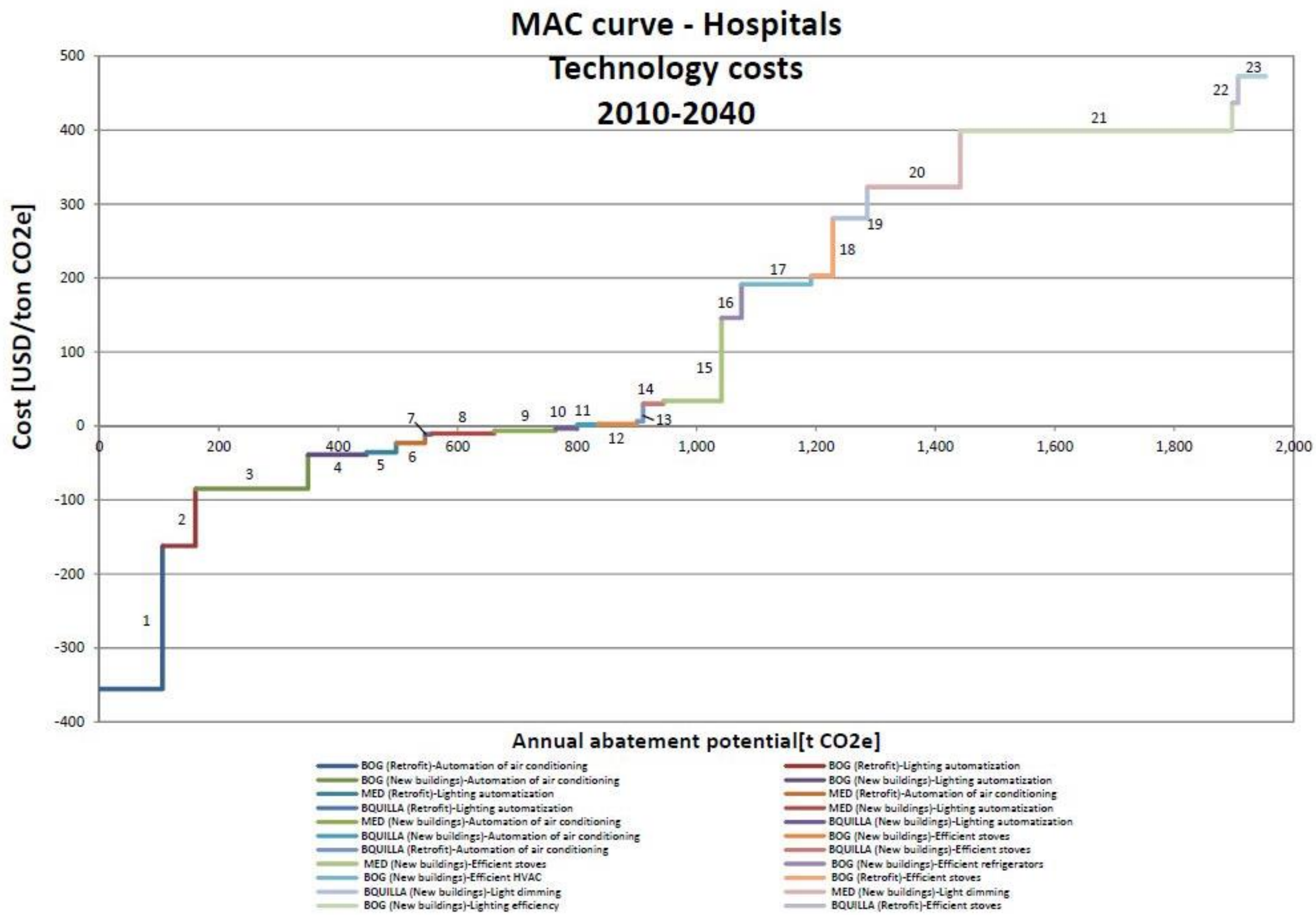


Table 16: MACC Input Information for Hospitals (Including Only Technology Costs)

No.	Mitigation Measure	Annual Potential (Tons CO_2e)	Cost ($/ton CO_2e)
1	Bogotá (Retrofit) Automation of air conditioning	105.72	-355.48
2	Bogotá (Retrofit) Automated lighting	55.21	-162.13
3	Bogotá (New buildings) Automation of air conditioning	188.21	-84.85
4	Bogotá (New buildings) Automated lighting	98.28	-38.70
5	Medellín (Retrofit) Automated lighting	49.55	-35.54
6	Medellín (Retrofit) Automation of air conditioning	48.39	-22.95
7	Baranquilla (Retrofit) Automated lighting	10.81	-11.27
8	Medellín (New buildings) Automated lighting	104.91	-10.28
9	Medellín (New buildings) Automation of air conditioning	102.46	-6.63
10	Baranquilla (New buildings) Automated lighting	36.62	-3.25
11	Baranquilla (New buildings) Automation of air conditioning	35.35	1.85
12	Bogotá (New buildings) Efficient stoves	64.69	2.78
13	Baranquilla (Retrofit) Automation of air conditioning	10.43	6.44
14	Baranquilla (New buildings) Efficient stoves	33.98	30.08
15	Medellín (New buildings) Efficient stoves	97.41	33.72
16	Bogotá (New buildings) Efficient refrigerators	33.30	146.14
17	Bogotá (New buildings) Efficient HVAC	116.65	191.65
18	Bogotá (Retrofit) Efficient stoves	36.34	203.24
19	Baranquilla (New buildings) Light dimming	57.66	280.73
20	Medellín (New buildings) Light dimming	155.85	322.92
21	Bogotá (New buildings) Lighting efficiency	455.27	398.95
22	Baranquilla (Retrofit) Efficient stoves	10.03	436.67
23	Medellín (Retrofit) Efficient stoves	46.00	472.63

Figure 12: MAC Curve for Hotels (Including Only Technology Costs)

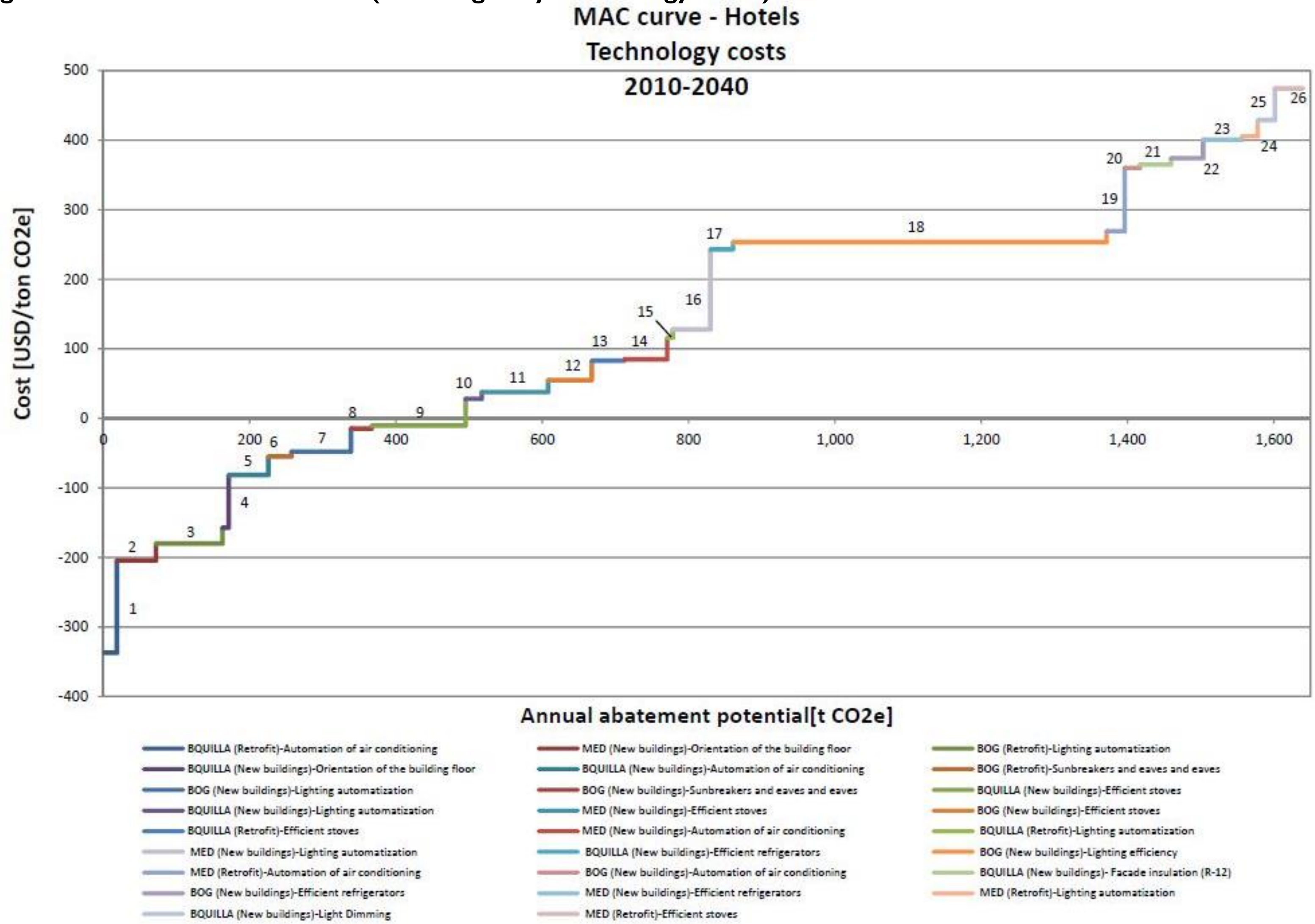


Table 17: MACC Input Information for Hotels (Including Only Technology Costs)

No.	Mitigation Measure	Annual Potential (Tons CO_2e)	Cost ($/ton CO_2e)
1	Baranquilla (Retrofit) HVAC automation	18.60	-337.06
2	Medellín (New buildings) Orientation of the building floor	53.27	-204.34
3	Bogotá (Retrofit) Automated lighting	90.90	-179.90
4	Baranquilla (New buildings) Orientation of the building floor	8.43	-157.28
5	Baranquilla (New buildings) HVAC automation	54.21	-81.52
6	Bogotá (Retrofit) Sunbreaks and eaves	31.80	-54.83
7	Bogotá (New buildings) Automated lighting	81.18	-47.81
8	Bogotá (New buildings) Sunbreaks and eaves	28.40	-14.57
9	Baranquilla (New buildings) Efficient stoves	128.33	-10.31
10	Baranquilla (New buildings) Automated lighting	22.16	28.06
11	Medellín (New buildings) Efficient stoves	90.73	37.87
12	Bogotá (New buildings) Efficient stoves	59.60	55.06
13	Baranquilla (Retrofit) Efficient stoves	44.04	82.75
14	Medellín (New buildings) HVAC automation	59.16	84.80
15	Baranquilla (Retrofit) Automated lighting	7.60	116.01
16	Medellín (New buildings) Automated lighting	51.50	127.79
17	Baranquilla (New buildings) Refrigeration efficiency	30.79	242.94
18	Bogotá (New buildings) Lighting efficiency	510.57	253.48
19	Medellín (Retrofit) HVAC automation	24.87	269.11
20	Bogotá (New buildings) HVAC automation	20.68	360.01
21	Baranquilla (New buildings) Facade insulation (R-12)	42.76	364.92
22	Bogotá (New buildings) Refrigeration efficiency	43.90	374.15
23	Medellín (New buildings) Refrigeration efficiency	53.02	400.69
24	Medellín (Retrofit) Automated lighting	21.65	405.52
25	Baranquilla (New buildings) Lighting dimming	23.13	428.76
26	Medellín (Retrofit) Efficient stoves	38.14	474.41

6. CO-BENEFITS

Colombia is not a large emitter of greenhouse gases, constituting only 0.37 percent of global emissions. However, it is carbon-intensive in terms of GHG emissions per unit of GDP. With increasing economic growth, Colombia could play a more significant role in future GHG emissions. . Implementation of mitigation actions would prepare for a more sustainable future, and support the growth of the energy efficiency industry, and allow other productive sectors to reallocate resources to be more efficient.

International competitiveness is a key issue for Colombia, which is in the process of negotiating free trade agreements with other trading zones. Addressing GHG emissions is often a critical point of discussion in trade negotiations.

Over the last five years, Colombia has played an important role in electricity generation within the Latin American region. Colombia's geography and hydrologic resources have filled the domestic demand for electricity and generated a surplus for sale to neighboring countries. Conservation of electricity in the country could decrease infrastructure costs and maintain foreign exchange earnings from electricity exports.

Implementation of carbon mitigation measures for buildings may improve the comfort, health, and productivity of occupants. Furthermore, some carbon mitigation options also reduce other pollutants that have negative health impacts and incur other economic and environmental damages. Energy efficiency measures for residential buildings can save low- and middle-income households a significant portion of their budgets (Universidad de los Andes 2013).

Lower natural gas consumption also reduces fugitive emissions caused by the extraction and transport of natural gas to the consumption site.[8] It may also reduce human exposure to natural gas leaks and carbon monoxide.

Replacing refrigerators and air conditioners with new technologies and adequately disposing older technologies reduces the emission of ozone-depleting substances that increase human exposure to ultraviolet radiation and decrease crop productivity (Robyn 2011).

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[8] According to the IPCC (2006), fugitive emissions of CO_2 during production, transport, and distribution averaged 3.618 grams CO_2/m^3 of produced natural gas.

7. CONCLUSIONS AND RECOMMENDATIONS

Key conclusions from the study:

- Top-down approaches to analyzing energy consumption in a particular sector can be useful if consolidated public data are disaggregated by city, productive sector, and energy sources.
- Survey data were limited, but included the most representative building types of the subsector analyzed.
- Calculating reference scenarios for GHG emissions in Colombia is difficult, as mitigation goals and targets are uncertain.
- Shopping centers, office buildings, hotels, and hospitals represented the largest portion of the tertiary sector in terms of area and energy consumption.
- Since 2007, energy consumption has decreased, largely due to changes in tenant behavior and use of new technologies.
- Construction subsector forecasts indicate considerable growth in Barranquilla and Medellín, while Bogotá is forecast to grow at a more moderate pace. GDP growth in the construction sector is likely to at least equal the average GDP growth of 5 percent per year. Construction of shopping centers, office buildings, and hotels is expected to grow steadily, while hospital construction will grow at a slower pace.
- Sixteen mitigation actions were evaluated, including architectural and energy efficiency measures. Results were compared against a BAU scenario to calculate mitigation potential.

By accounting for overlap and interactions among the mitigation measures, ten groups of reduction options were established for each subsector in the three cities. For new and existing buildings, two sets of MACCs were developed—one for total costs and the other for technology costs only. There were sixty measures per building category, half pertaining to new buildings and half to existing buildings.

For each subsector, the MACCs covered thirty six of the mitigation measures, with the largest number for shopping center). The remaining mitigation options were excluded because they were not cost-effective in Colombia due to high capital or operating costs or low mitigation potential.

Lighting measures were the most important reduction options for all four subsectors. Lighting automation had high mitigation potential and negative net costs for both new and existing buildings. Lighting efficiency had the highest mitigation potential for new buildings. Although light dimming did not offer as large a mitigation potential as the other lighting options, it could produce some CO_2 savings.

Design measures were the most expensive to implement and operate in all four subsectors. For example, window glazing was in the top right-hand area of the MACCs and only offered moderate mitigation potential.

The most energy inefficient building subsector in Bogota was hospitals. Site visits and secondary data indicated that the health sector had not adopted many mitigation actions, despite significant mitigation opportunities. In Medellín, shopping centers were the most energy inefficient since most were open and had higher inside air-conditioning requirements than shops in enclosed shopping centers. In Barranquilla, office buildings had the highest energy consumption per square meter. Most of the office buildings surveyed had glass facades with poor bioclimatic performance.

of the addition of isolation panels to facades with was more effective for residential units than commercial units. Commercial buildings had more air conditioning requirements and less contact between the building envelope and the occupied space than residential units. Therefore the impact of architectural elements (facades and windows.) was more important for residential buildings than commercial buildings.

We assumed that mitigation measures with net technology costs under $100/ton could be implemented, considering co-benefits, but excluding labor costs. The mitigation potential in 2040, listed in decreasing order of mitigation potential in tons, was projected at:

- Office buildings: 63.13 percent (657,023 tons–1,792,000 tons)
- Shopping centers: 10.92 percent (536,262 tons–602,000 tons)
- Hospitals: 11.5 percent (242,490 tons–274,000 tons)
- Hotels: 12.56 percent (161,764 tons–185,000 tons)

If total costs (technology and labor) are considered, the mitigation potential was slightly different

- Office buildings: 58.92 percent (731,122 tons–1,792,000 tons)
- Shopping centers: 8.47 percent (551,010 tons–602,000 tons)
- Hospitals: 11.5 percent (242,490 tons–274,000 tons)
- Hotels: 10.54 percent (165,501 tons–185,000 tons)

The mitigation potential in office buildings was by far the largest due to the high growth forecast and untapped energy efficiency opportunities. The availability of land for office buildings has been low over the last 30 years because much land has been used for housing. As a result, many small businesses had to locate in suburban areas. With the growing economy, however, many multinational companies have established operations in Colombia. The projected total growth in office space over the next 30 years is 200 percent in Bogotá, 158 percent in Medellín, and 400 percent in Barranquilla.

The majority of the mitigation options considered were above the 10 percent savings target established by PROURE (the reference scenario). Considering technology and labor costs of the mitigation measures, shopping centers were the only subsector that did not meet this target. Conversely, the mitigation potential of office buildings far exceeded the PROURE target. The mitigation potential of hotels and hospitals was also consistently above the target. The MACCs in this report may be used to assess the government's GHG savings target for commercial buildings. Furthermore, the PROURE mitigation target for buildings could be increased.

The study team made the following recommendations:

- Future regulatory efforts for carbon mitigation should consider emission baselines. It takes considerable effort to set GHG emission baselines, due to the lack of data and data inconsistencies across cities and subsectors. Data were particularly difficult to obtain for cities, such as Barranquilla.
- A MACC is a useful tool to set general priorities for mitigation actions. However, it should be followed with a more detailed study to examine specific options in detail, including implementation feasibility.

- Sustainability of the built environment is part of the agenda of multiple public agencies. Efforts should be made to unify and integrate the many national and local initiatives.
- The National Seismic Norm NSR-10 (*Norma Sismo Resistente,* updated in 2010) addressed some sustainability issues and it is mandatory for all buildings. Consequently, it is a very important requirement for future regulations addressing GHG mitigation.

There should be clear metrics to evaluate compliance and performance of GHG mitigation regulations. Nationally Appropriate Mitigation Actions (NAMAs) should include substantial stakeholder involvement, which will require increasing stakeholders' understanding of roles, expected performance, and measurement. Many discussions have been held in Colombia on actions and incentives, but relatively little on how to motivate and measure compliance.

In Colombia, informal buildings without a construction license constitute nearly 50 percent of total construction. In the commercial sector, informal buildings have been built in inappropriate areas, including places with high geological risks. The materials used in informal construction often do not comply with minimal technical specifications. Energy use in informal settlements often relies on carbon-intensive technologies and energy consumption is unregulated and unmeasured. Since informal commercial construction was not included in this study, further work is needed to assess the problems and potential solutions. The informal sector should be viewed as an opportunity for improving a large proportion of residential and commercial buildings.

The high cost of implementing mitigation technologies for construction is a major barrier. Since commercial construction is expected to grow by 68 to 97 percent from 2010 to 2040, efforts directed at new development may have a more significant impact than efforts to retrofit existing buildings. However, retrofit measures should also be considered because they have important co-benefits.

GHG mitigation measures face some constraints for successful implementation in Colombia. The construction industry is not yet ready to implement these measures. Knowledge of sustainable construction technologies is limited and not well distributed around the country. The local construction industry needs further support to enhance its technical capacity and provide greater access to the wider green technology market. Some Leadership in Energy and Environmental Design (LEED) initiatives have helped make developers more familiar with sustainability issues[9] . However, establishing a local sustainable construction certification would be desirable. The Colombian government is currently in the process of establishing a Colombian Environmental Seal for Sustainable Buildings (SAC-ES). The committee is led by the Ministry of Environment, Housing and Territorial Development and the Colombian Institute of Technical Standards (Icontec) with representatives of academia, trade unions, industry and the public sector.

Efforts to improve management practices in construction are also needed. Design, build, and operate projects may be more attractive for developers interested in implementing energy and water conservation measures.

Some other issues need to be considered, such as proper disposal of LED and CFL bulbs containing mercury or other hazardous substances. Colombia does not currently recycle solid wastes and has few specialized places for hazardous waste disposal. Facilities to safely handle spent light bulbs and other equipment need to be developed (Secretaría de Integración Social 2013).

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[9] LEED is a green building tool that addresses the entire building lifecycle recognizing best-in-class building strategies. See Appendix 1.

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