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Marginal Abatement Costs Curve (MACC) for Carbon Emissions Reduction from Buildings: An Implementation for Office Buildings in Colombia

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***Abstract*—The building industry is a significant contributor to global Greenhouse Gas (GHG) emissions and is responsible for approximately 30% of global CO_2 emissions. In order to evaluate energy efficient practices in the building sector, the authors propose a Marginal Abatement Cost Curve (MACC), assessing the costs and reduction potentials of abatement measures, based on data obtained from Building Information Modelling (BIM). This integrated approach combines a building stock forecast with CO_2 abatement measures modelled with BIM, providing more valuable insights to policy makers for the achievement of emission reductions in a cost-effective manner. With the financial support of the Colombian Ministry of Environment, the model is applied up to 2040, capturing the building stock of three major cities representing the diversity of the Colombian climate. Results are given as a MACC for reduction of CO_2 emissions from Colombian office buildings, showing that there is a significant cost-effective potential that could be reached through abatement measures not yet implemented in the country. The application of the model is flexible given that results can be produced for any building stock, for different building types, and for the performance of individual measures in any building type.**

***Keywords*—Building Information Modeling (BIM), Greenhouse gases (GHG), Marginal Abatement Costs Curve (MACC), Cost-effectiveness.**

I. Introduction

Global energy use and its corresponding emissions are expected to grow and, in a context of limited budgets and divergent interests, decision makers face several difficulties in finding appropriate solutions to Greenhouse Gas (GHG) mitigation. Likewise, the building sector is an important consumer of energy, and low-carbon measures in this sector often compete with regard to multiple aspects such as the costs of various technology options, mitigation potentials, and levels of uptake, among others.

The building sector has multiple environmental impacts [1], including high energy consumption and its related GHG emissions [2], and there is a global interest in promoting energy efficient practices in this industry for two main reasons: firstly, according to the Buildings and Climate Change report of United Nations Environment Programme (UNEP) [3], the building sector contributes up to 30% of global annual GHG emissions. Secondly, sustainable performance is a major factor when examining the feasibility of construction projects in terms of their life cycle performance [4] [5].

Priorities and strategies to introduce low carbon technologies often compete with regard to multiple aspects such as the costs of various technology options, mitigation potentials, and levels of uptake, among others. In order to overcome these challenges, policy makers have made use of models and tools such as Marginal Abatement Cost Curves (MACCs), presenting the expenditure necessary to abate a defined amount of carbon emissions according to different abatement measures. MACC may be the most accepted tool for identifying satisfactory solutions for different sectors as in the construction industry.

On the other hand, new technologies such as Building Information Modelling (BIM) are currently being used for managing the information in the Architecture, Engineering, and Construction (AEC) industry to integrate different design aids through simulations – like energy use assessments – and to assess projects from a holistic perspective [6], but few papers related to GHG emissions from the building sector have based their assessments on BIM and MACC simultaneously.

In this research, an innovative methodological approach has been proposed for the MACC model, based on the integration of BIM with a future building stock model, to evaluate abatement measures to help stabilize CO_2 emissions. To evaluate the flexibility and usefulness of the proposed MACC methodology, it was applied to three Colombian cities representing Colombian climate diversity over a 30-year horizon.

The total GHG emissions of Colombia account for only 0.37% of total GHG emissions worldwide. In absolute terms, Colombia accounted for 18×10^4 Gg of $CO_{2\text{-eq}}$ in 2004, while in the same year this value was $4{,}900 \times 10^4$ Gg of $CO_{2\text{-eq}}$ worldwide. However, Colombian energy use and corresponding emissions are expected to grow up to 60×10^4 Gg of $CO_{2\text{-eq}}$ in 2040 [7]. Therefore, public and private actors in the country are beginning to recognize the importance of mitigation actions to reduce the effects of climate change [8].

A recent study performed by the UPME (Unidad de Planeación Minero Energética – Mining and Energy Planning Unit) concerning Bogotá, Medellín, and Barranquilla showed that the non-residential sector (education, health, commerce,

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and public institutions) consumed over 30% of total national energy demand in 2007. The study also concluded that the office buildings sector in Bogotá had the largest share of energy demand in the country [9].

This study developed the CO_2 marginal cost levels for fourteen CO_2 emission reduction measures in all the office buildings of three Colombian cities up to 2040. Some abatement measures are related to changes in building design for natural lighting and ventilation, the adoption of high efficient Heating, Ventilation, and Air Conditioning (HVAC) systems, new lighting technologies (LEDs in this study.), and low energy consumption in standby mode, among others.

In the following section, the authors describe the context and general background of the published works on the topic available in the literature. In the second and third sections, the fundamentals of the MACC method, the proposed methodology, and the process of estimating the potential impacts are briefly explained. In the fourth and fifth sections, the proposed method is applied to Colombian office buildings and the main assumptions are described. Finally, the results are presented. The paper concludes with some general remarks on the methodology and its application to the Colombian office buildings sector.

II. Literature Review of the MACC of Carbon Emissions from Buildings

In 1948, the marginal cost was defined by Paulson as "the extra cost added to the total cost for a unit of output" [10]. Earlier this century, MACC represented the marginal cost to a firm of avoiding the last unit of emission, and then MACC was adopted for climate policy purposes and became a standard tool for analysing the impacts of the Kyoto Protocol [11].

MACC enables a comparison of the cost-effectiveness of mitigation options in different sectors, for example agriculture [12] and shipping [13], among others, and the international literature has shown several attempts to develop MACCs for building sector in different countries. The first application of MACC – although it was not yet called MACC at that time – in the commercial building sector was presented by Mortimer et al. in 1998, whose results of an initial assessment of CO2 emissions in the UK were analysed with a MACC that ranked the energy efficiency measures capable of reducing CO2 emissions in order of decreasing cost-effectiveness [14].

Lee and Yik (2002) were interested in analysing, through a MACC, the main differences between the impacts of regulatory (building energy codes) and voluntary (building environmental performance assessments) approaches on energy consumption worldwide [15]. Ürgue-Vorsat et al. (2008) carried out an assessment for the Intergovernmental Panel of Climate Change (IPCC), producing a global MACC for the building sector based on studies realized in 80 countries, and showed that the assessed developing countries – Myanmar, India, Indonesia, Argentine, Brazil, China, Ecuador, Thailand, Pakistan, and South Africa – presented the largest cost-effective potential [16]. De Melo et al. (2013) applied a multi-criteria analysis and MACC to evaluate public policy mechanisms to promote the dissemination of energy efficiency and on-site renewable energy sources technologies in the Brazilian buildings sector [2].

To the best of the authors' knowledge, only two researchers have used BIM to develop a MACC for buildings. Ibn-Mohammed et al. (2013) analysed the difference between operational and embodied emissions, using a model of a building in the UK [17], and Pountney (2012) compared a genetic algorithm to a MACC approach for an office building modelled with the software Simplified Building Energy Model (SBEM), also in the UK [18]. Nevertheless, many authors, such as Kuusk *et al*. (2014), have modelled reference buildings in order to evaluate energy-saving measures but have not related their findings to a MACC [19].

III. Traditional MACC Model

MACC is considered one of the most useful methodologies for evaluating GHG abatement measures and several studies have applied it for assessing opportunities to mitigate GHG emissions [2]. MACC offers, in a graphical representation, the GHG mitigation potential and the marginal costs of abatement measures in a period of time, and each numbered line represents the results of an abatement measure. The width of the line represents the GHG abatement potential, which is the amount of CO2 in tonnes that could potentially be abated by the measure, and the height of the line represents the marginal cost of abating a tonne of CO2 in USD per tonne (Fig. 1).

The measures are ranked according to their marginal costs. More cost-effective measures are on the left-hand side; they have negative abatement cost, have the potential to save money as well as CO2, and are called win–win measures [2].

The marginal cost is the Cost of Abating a Tonne of CO2 (CATCH), and its formulation for each abatement measure is presented in (1), where ΔE is the abatement potential of CO2 emissions (tonnes of CO2), ΔC the associated lifetime cost ($), and ΔB the economic benefit due to the implementation of the measure [13].

$$\text{CATCH} = \frac{\Delta C - \Delta B}{\Delta E} \quad (1)$$

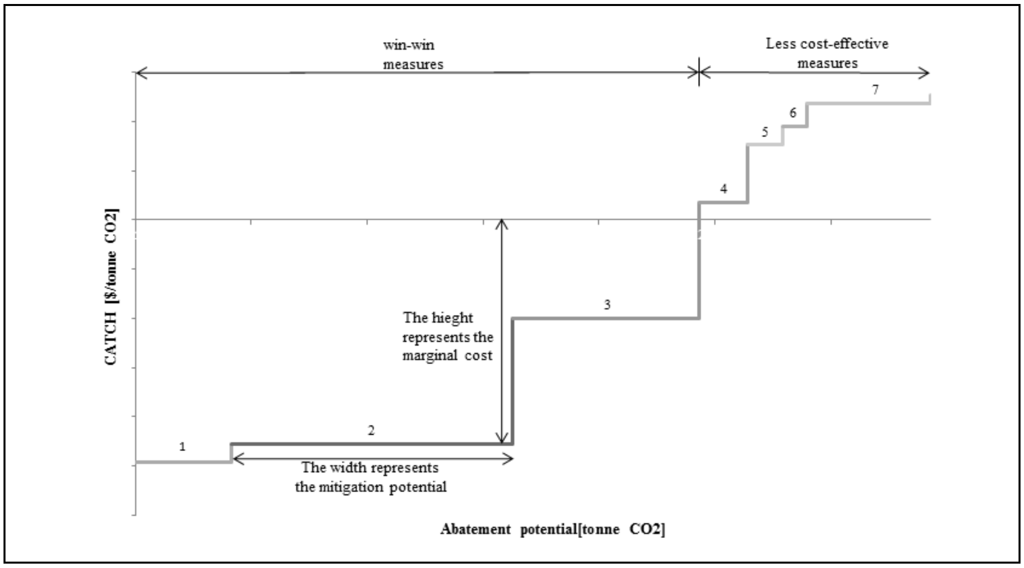

Figure 1. Marginal abatement cost curves representation

IV. The proposed MACC Model of Carbon Emissions from Buildings

In this study, MACC estimation is based on a bottom-up analysis of abatement measures and the overall approach is illustrated in Fig. 2. The first step is to develop a broad base of data regarding the economic, demographic, and technical conditions of the cities to be analysed. The second step is based on BIM and an energy simulation tool and develops a base of data including estimates of the energy savings, specified for each city, and the implementation costs of each abatement measure. The third step is an estimation of the building forecasts for the calculation of the potential impacts in terms of costs and CO_2 mitigation. Finally, from these results, the MACC method is applied in order to create a portfolio of options that can assist in the selection of the best measures to be implemented in each city.

A detailed description of each step within the methodological approach is presented below:

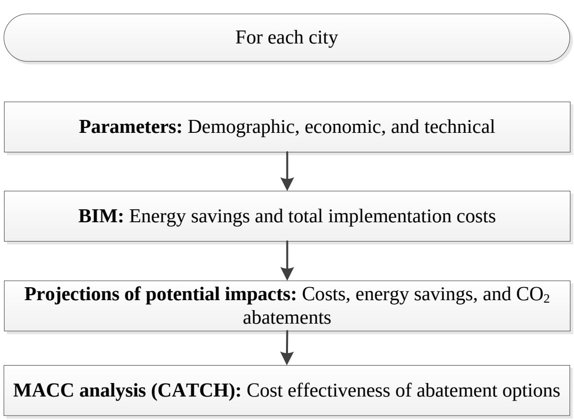

Figure 2. Flowchart of the methodological approach

A. *Parameters*

Demographic, economic, and technical inputs are necessary for the construction of MACC.

Demographic parameters: Building growth rates are used to find the number of buildings in operation for a given year in a given city. The forecasting model generates representations of future stocks using the building stock of each city in the first year (s_1) and its annual growth rate (g), which includes a correction for the demolition rate until the last year (T).

Economic parameters: The energy prices (ep) are used in the model to compute the costs and benefits of the mitigation measures. The costs and benefits are converted to the present value using an annual discounting rate (r) to compare measures in a homogenous way. The levels of uptake of the cost-effective measures (in terms of the percentage of buildings) reflect the widespread implementation of the new technologies. The levels of uptake vary for new (un_i) and existing (ue_i) buildings and therefore they are determined for both of them.

Technical parameters: The emission factors (ef), in terms of the emission of CO_2 for each unit of energy used, are assumed for all fuels: electricity, natural gas, and coal, among others.

B. Building Information Modelling (BIM)

In order to determine the energy savings of the abatement measures (Δes) in each city, some existing buildings should be selected as the more representative buildings in each city to be modelled in BIM. Primary data are obtained from energy simulations using an energy calculation tool, called eQUEST®, integrated within the BIM models of the representative buildings. In the BIM models, the values for technical, technological, architectural and operational characteristics and local conditions – such as lighting and temperature – are implemented for each city, allowing the comprehension of the behaviour of each abatement measure in each city (Fig. 3). The operational profiles (operation time and loads) are assumed to be the same as in the existing buildings modelled with BIM, and for future stocks it is assumed that the operational profiles are unchanged.

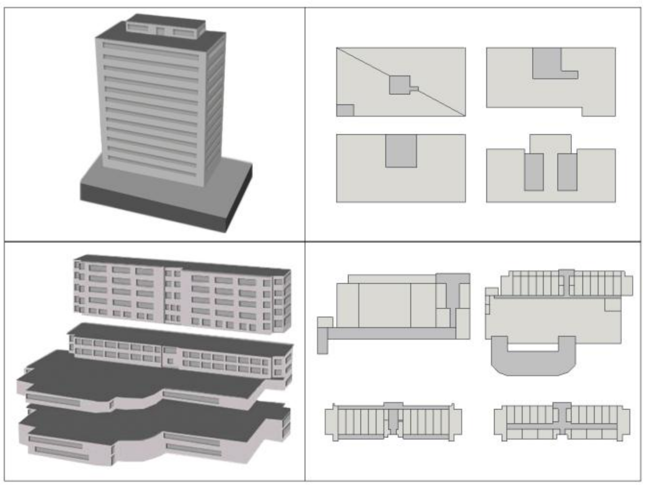

Figure 3. BIM models of two office buildings integrated with the eQUEST® energy simulation tool.

The analysis includes numerous abatement measures. For some of them, implementation costs vary for new (ΔC_n) and existing (ΔC_e) buildings, and therefore they are determined for both of them.

C. Projections of Potential Impacts

The forecasting process consists of the projection of potential impacts of implementing each measure on the building stocks. The model starts with the stock of the initial year, and the number of buildings in a city in the following year is given by adding new buildings to the last year's stock. The total costs ($\Delta C_{m,i}$), benefits ($\Delta B_{m,i}$), and emission reductions ($\Delta E_{m,i}$) for each measure and year, where *m* is the index for the measure and *i* the corresponding year, are found and stored through iterations using the values obtained from the previous steps of the methodological approach (Fig. 4).

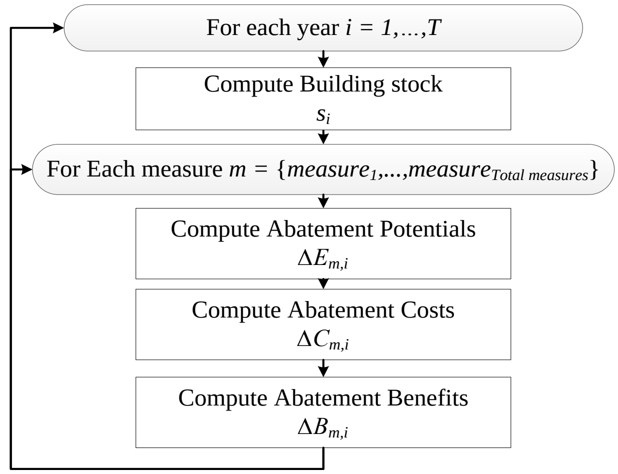

Figure 4. Flowchart for computing the projections of potential impacts

The pseudo code for computing projections of potential abatements is shown below, where *M* is the set of total abatement measures analysed.

$$M = \{measure_1, \dots, measure_m, \dots, measure_{totalmeasures}\}$$

$$\Delta E_{m,1} = ef_m \cdot \Delta es_m \cdot s_1 \cdot ue_1; \quad \forall m \notin M \tag{2}$$

$$\Delta C_{m,1} = \Delta cn_m \cdot s_1 \cdot un_1; \quad \forall m \notin M \tag{3}$$

$$\Delta B_{m,1} = ep_m \cdot \Delta es_m \cdot s_1 \cdot un_1; \quad \forall m \notin M \tag{4}$$

For $(i = 2, T, +1)$

$$s_i = s_{i-1} \cdot (1+g) \tag{5}$$

For $(m = 1, totalmeasures, +1)$

$$\Delta E_{m,i} = ef_m \cdot \Delta es_m \cdot ((s_i - s_{i-1}) \cdot un_i + s_{i-1} \cdot ue_i) \tag{6}$$

$$\Delta C_{m,i} = \Delta cn_m \cdot (s_i - s_{i-1}) \cdot un_i + \Delta ce_m \cdot s_{i-1} \cdot ue_i \tag{7}$$

$$\Delta B_{m,i} = ep_m \cdot \Delta es_m \cdot ((s_i - s_{i-1}) \cdot un_i + s_{i-1} \cdot ue_i) \tag{8}$$

EndFor

EndFor

Equation (5) computes the number of buildings in a city in the corresponding year by adding new buildings to the previous year's stock. Equations (2) and (6) compute the expected reduction of CO2 emissions due to the implementation of an abatement measure during the first and the other years, respectively. The first term of Equation (6), $(s_i - s_{i-1}) \cdot un_i$, represents the new buildings implementing the abatement measure and the other term, $s_{i-1} \cdot ue_i$, represents the existing buildings implementing the abatement measure; efm represents the emission factor used for the abatement measure m, Δesm is the energy saving from implementing m, si is the building stock in the year i in cubic metres of floor area, uni is the level of uptake for new buildings in the year i, and uei is the level of uptake for existing buildings in the year i.

In the same way, Equations (3) and Line (7) compute the lifetime cost of implementing the measure on the building stock ($), where Δcnm represents the cost of implementing the measure m in new buildings (USD/m^2), and Δce_m represents the cost of implementing the measure *m* in existing buildings (USD/m^2).

Finally, Equations (4) and (8) compute the economic benefit during the operational lifetime of the building stock due to the implementation of a measure, including the benefit due to electricity or fuel cost savings. In (4), ep_m is the energy price of the fuel used for the implementation of the measure *m*.

D. MACC Analysis

Once the projections of potential impacts (the costs, benefits, and emission reductions.) during the analysed period T have been obtained, the costs and benefits are discounted to a present value using the annual discounting rate r. Equation (9) gives the final results of the values of CATCH for each abatement measure. To provide a generalized comparison of the abatement measures, the detailed pairs of $CATCH_m$ and $\sum_{i=1}^{T} \Delta E_{m,i}$ for each city are plotted to produce the MACC.

$$CATCH_m = \frac{\sum_{i=i}^{T} (\Delta C_{m,i} - \Delta B_{m,i}) \cdot (i+r)^{-i}}{\sum_{i=1}^{T} \Delta E_{m,i}} \qquad (9)$$

It is important to consider that data on emission reduction effects and costs are gathered from actual projects, and these data are considered to be of good quality. However, the extrapolation of cost and energy savings from sample buildings to an entire stock introduces uncertainty. On the other hand, it is noted that the values for individual buildings may vary significantly, but the effects produced by the estimated values used in this study are expected to be more moderate because the results are analysed from a global perspective.

V. Implementation of the Proposed MACC Analysis in Colombian Office Buildings

A MACC analysis for office buildings in Bogotá, Medellín, and Barranquilla is presented, since these three major cities represent Colombian climate diversity. Each of the input parameters is described and quantified below, including the source from which they are obtained or the methodology used for its estimations.

Predicting building development in Colombia is a complex and highly challenging task and most published building forecasts are short term. For that reason, initial values for the office buildings stocks in 2010 (Table 1) were obtained from the National Building Census performed by the National Department of Statistics [20].

TABLE I. OFFICE BUILDINGS STOCK IN 2010 (S_{2010}), IN TERMS OF FLOOR AREA [20].

Value	City		
	Bogotá	*Medellin*	*Barranquilla*
Office buildings stock 2010 (m^2)	15,418,715	4,176,165	422,885

The values for annual growth, in terms of percentage of building floor area, have been obtained from the "Colombian Strategy for Low-Carbon Development" study (ECDBC) of the Colombian Ministry of the Environment [7] and are based on the estimation of the construction sector's GDP growth. The annual growth rates for the office building stocks are presented for each year from 2010 until 2040 (Table 2). For brevity, the rates are provided as year-on-year percentages averaged over five-year intervals, showing how the growth rate will increase slightly in the next years.

TABLE II. YEAR-ON-YEAR GROWTH RATES [G] EXPRESSED AS A PERCENTAGE OF BUILDING FLOOR AREA, FIVE-YEAR AVERAGES [7].

Value	Year					
	2010–2015	*2015–2020*	*2020–2025*	*2025–2030*	*2030–2035*	*2035–2040*
Growth rates (%)	4.40	4.78	5.12	5.46	5.35	5.09

The energy prices [*ep*] used in the model are presented in Table 3 [21] and the costs and benefits are converted to a present value using an annual discounting rate [*r*] of 10%, as in the ECDBC study [7].

TABLE III. ENERGY PRICES [EP] IN 2010 [21].

Value	City		
	Bogotá	*Medellín*	*Barranquilla*
Electricity (USD/kWh)	382	403	386
Natural gas (USD/m3)	984	854	887

The levels of uptake of cost-effective measures for new (un_i) and existing (ue_i) buildings were provided by the Colombian government (sponsor of the ECDBC study.) and applied in all measures where it was technically feasible; for example, changing the orientation of the building floor was not possible for existing buildings (Table 4).

TABLE IV. LEVELS OF UPTAKE (%) OF COST- EFFECTIVE MEASURES FOR EXISTING [*UE*] AND NEW BUILDINGS [*UN*]

City	Existing Buildings			New Buildings		
	2010–2018	*2019–2025*	*2025–2040*	*2010–2018*	*2019–2025*	*2025–2040*
Bogotá	20%	30%	40%	50%	70%	100%
Medellín	20%	30%	40%	50%	70%	100%
Barranquilla	20%	30%	40%	50%	70%	100%

The emission factors (*ef*) assumed in the model are set as to 48.61 $GgCO_2$/PJ for electricity in all the cities, 60.23 $GgCO_2$/PJ for natural gas in Bogotá, and 55.34 $GgCO_2$/PJ for natural gas in Medellín and Barranquilla [7].

Four existing office buildings (two located in Bogotá, one in Medellín, and one in Barranquilla) were selected as the more representative office buildings in each city and 14 abatement measures were modelled in BIM.

- Roof insulation (R–20): the installation of 4 inches of polystyrene on the roof
- Façade insulation (R–12): the installation of 2 inches of polyurethane on the facade
- Single-layer low-emissivity glass: the installation of low emissivity glass of 1/4 inch
- Double-layer low-emissivity glass: the installation of double glass with 1/4 inch of vacuum chamber and 1/8 inch of low emissivity glass
- Double-tinted glass: the installation of tinted double glass with 1/4 inch of vacuum chamber and 1/4 inch of low emissivity glass
- Sunbreaks and eaves: the installation of window shades on the faces of the buildings most exposed to sunlight
- Orientation of the building floor: the definition of the orientation depending on the building's location
- Lighting efficiency: the replacement of all bulbs with LED bulbs
- Light dimming: the installation of dimmers that detect natural light and, depending on its level, increase or decrease the lighting intensity
- Automated lighting: the installation of occupation sensors
- HVAC premium: the replacement of old air conditioning systems
- HVAC economizers: the installation of devices for AC equipment that recycle air from outside
- Automation of air conditioning: the installation of entrance cards or occupation sensors in mechanically ventilated areas
- Infrastructure improvements: the replacement of old structural wiring and data centres

In the proposed model, some assumptions were considered, and the MACC explicitly reflects the economic feasibility of the measures, while organizational, legal, and other barriers to implementing measures are not considered here.

The costs of the measures, a fixed price per square metre of floor area, have been collected from various suppliers and manufacturers including technology and labour costs for installation. In order to avoid overlapping between similar abatement measures, the measures were classified into nine categories and the most cost-effective measure from each category was selected and included in the final MACC (Table 5).

TABLE V. COSTS OF THE ABATEMENT MEASURES ASSESSED

Category	Abatement measure *(m)*	Costs [USD/m^2] *new buildings (Δcn)*	Costs [USD/m^2] *existing buildings (Δce)*
1	• Roof insulation (R–20) • Façade insulation (R–12) • Single-layer low-emissivity glass • Double-layer low-emissivity glass • Double-tinted glass • Sunbreaks and eaves	16.97 26.55 48.15 120.38 168.53 114.72	16.97 26.55 48.15 120.38 168.53 114.72
2	• Orientation of the building floor	0.00	N/A
3	• Lighting efficiency	24.20	29.82
4	• Light dimming	325.41	325.41
5	• Automated lighting	0.88	0.88
6	• HVAC premium	3.96	5.66
7	• HVAC economizers	3.33	3.33
8	• Automation of air conditioning	0.88	0.88
9	• Infrastructure improvements	22.63	22.63

Not all conceivable abatement measures have been included in this analysis. A great effort has been made to be realistic in the approach and therefore only widely accepted measures have been included. Measures and technologies currently in development and available in the foreseeable future have been omitted from the analysis. It is considered unlikely that any design measure of significant potential has been omitted.

VI. Results of the MACC Analysis Implementation in Colombian Office Buildings

The MACC model proposed has been applied for a time span of 30 years to office buildings in three major cities in Colombia: Bogotá, Barranquilla, and Medellín. A selected marginal cost criterion was applied, determining that abatement measures with a CATCH of less than 300USD/tonne should be applied to the stock, generating the curve presented in Fig. 5. The marginal abatement costs curve proved to be negative for 11 of 25 abatement measures (win–win measures), representing a total mitigation of 20,000 tonnes of CO_2 from 2010 to 2040.

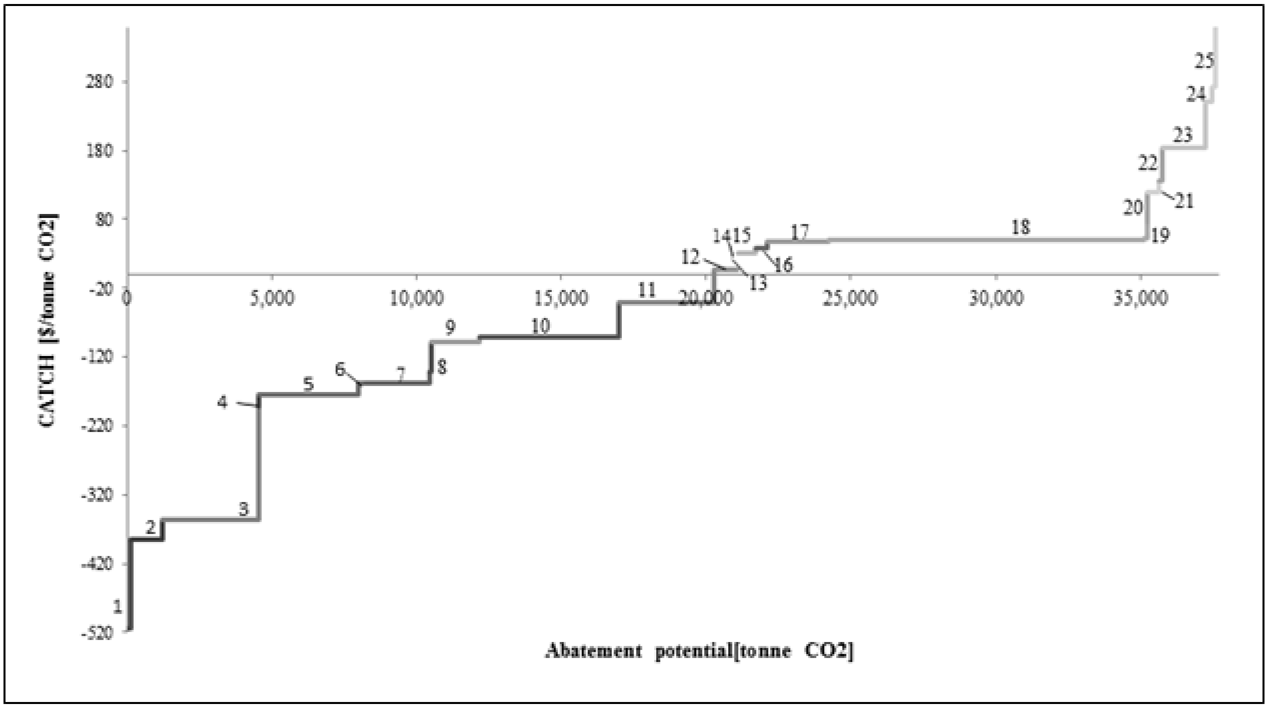

Figure 5. MACC related to office buildings in Bogotá, Medellín, and Barranquilla

For a better understanding of the resulting MACC curve, key details are presented in Table 6, which shows the estimations of the potential impacts of each abatement measure in terms of its CATCH and its abatement potential.

TABLE VI. MACC INPUT INFORMATION

No.	*Abatement Measure*	Abatement Potential *(tonnes CO_2)*	CATCH *(USD/tonne CO_2)*
1	Barranquilla: (retrofit) automation of air conditioning	98.78	–514.41
2	Bogotá: (retrofit) automated lighting	1124.94	–384.11
3	Bogotá: (retrofit) light dimming	3316.97	–356.54
4	Barranquilla: (new buildings) orientation of the building floor	18.96	–191.35
5	Bogotá: (new buildings) orientation of the building floor	3431.72	–174.87
6	Barranquilla: (new buildings) automation of air conditioning	244.23	–158.19
7	Bogotá: (retrofit) facade insulation (R-12)	2207.13	–157.16
8	Medellín: (new buildings) orientation of the building floor	69.27	–142.19
9	Bogotá: (new buildings) automated lighting	1646.21	–98.29
10	Bogotá: (new buildings) light dimming	4853.96	–91.24
11	Bogotá: (new buildings) facade insulation (R-12)	3229.86	–40.22
12	Medellín: (new buildings) light dimming	643.77	7.20
13	Barranquilla: (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	2145.93	47.07
18	Bogotá: (new buildings) lighting efficiency	10866.94	50.85
19	Medellín: (new buildings) automation of air conditioning	132.52	51.51
20	Barranquilla: (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	1466.43	183.93
24	Barranquilla: (new buildings) lighting efficiency	273.65	250.98
25	Medellín: (retrofit) automation of air conditioning	84.29	271.69

The highest potential for CO_2 mitigation is associated with lighting efficiency, light dimming, and orientation of the building floor, all of them for new buildings in Bogotá. This occurs due to the large amount of floor area expected to be constructed in Bogotá – almost 30,000,000 m^2 in 30 years. Regarding abatement costs, the most cost-effective options are automation of AC in Barranquilla, automated lighting in Bogotá, and light dimming in Bogotá, all of them for retrofits.

VII. Discussion

A summary of the win–win abatement measures of each city is shown in Table 7. As can be seen, automation of air conditioning for both retrofits and new buildings is a cost-effective measure in Barranquilla due to its hot weather. In the case of Bogotá, the evaluation points to the importance of more stringent standards for lighting and facade insulation for both retrofits and new buildings. In Medellín, as in the other two cities, orientation of the building floor of new buildings is the most attractive measure from the financial point of view due to the assumption that the total cost of this measure is zero.

These results demonstrate that the most cost-effective abatement measures in the three cities are affected by the diversity of the Colombian climate; thus the proposed model is flexible enough to be implemented in different demographic, economic, and technical contexts.

TABLE VII. WIN-WIN ABATEMENT MEASURES IN EACH CITY

City	*Retrofit*	*New buildings*
Barranquilla	Automation of air conditioning	Orientation of the building floor Automation of air conditioning
Bogotá	Automated lighting Light dimming Facade insulation (R-12)	Orientation of the building floor Automated lighting Light dimming Facade insulation (R-12)
Medellín		Orientation of the building floor

VIII. Conclusions

In this research, an innovative methodological approach has been proposed for the MACC model, based on the integration of BIM with a future building stock model, to evaluate abatement measures to help stabilize CO2 emissions from the building sector. In that way, the updated building stock development is combined with new data for the costs and effects of emission reduction options.

The methodology demonstrates its effectiveness in helping decision makers to evaluate low carbon measures in the building sector and to articulate preferences according to different competing aspects (i.e. CO2 mitigation, economy, etc.) with broad applicability. The results show the flexibility in the application of the model, because they can be produced for any building stock, for different building types, and for the performance of individual measures in any building type.

To evaluate the flexibility and usefulness of the proposed MACC methodology, it was applied to three Colombian cities, Bogotá, Barranquilla, and Medellin, over a 30-year horizon. This study developed the CO_2 marginal cost levels for fourteen CO_2 emission reduction measures in all of the office buildings in these cities, showing that there is a significant potential for cost-effective CO_2 emission reduction for the office building industry in Colombia and that the abatement potential is achievable at low or moderate cost:

1. Eleven win–win measures are currently available to the Colombian building sector, representing a total mitigation of 20,000 tonnes of CO2 from 2010 to 2040.
2. The differences between the most cost-effective abatement measures in the cities are affected by the diversity of the Colombian climate: automation of air conditioning is most cost-effective in Barranquilla, the city with hot weather, and more stringent standards for lighting and insulation are most effective in Bogotá, the city with cold weather.
3. Taking the right decision regarding the orientation of the building floor in new buildings is the most attractive abatement measure from the financial point of view.
4. The alternatives with the largest mitigation potential are lighting efficiency, light dimming, and orientation of the building floor, all of them for new buildings in Bogotá, due to the large amount of floor area expected to be constructed in Bogotá.
5. The results reveal that there is no "silver bullet" for reducing the emissions from the building stock and that a wide range of measures are needed to obtain significant reductions.

It is concluded that the presented methodology and data will be very useful for assisting the industry and policymakers in selecting cost-effective solutions for reducing GHG emissions from the office building sector, as well as for different building types.

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