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Applications of Marginal Abatement Cost Curve (MACC) for Reducing Greenhouse Gas Emissions: A Review of Methodologies

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ABSTRACT

A wide range of Marginal Abatement Cost Curve (MACC) methods for reducing greenhouse gas (GHG) emissions has been introduced in various academic literature in the last decade to address various issues, to use different calculable logic, producing different results and implications. A detailed review has not been carried out on the application of MACC in terms of types of emissions, country/sector, and methodology used. This study is aimed at identifying, interpreting, and clarifying currently available literature on MACCs development from 2010-2020 by reviewing the previous applicability of three analytic dimensions including Greenhouse Gas (GHG) emission type, research objects, and modeling methodologies from top-down and bottom-up methods, providing researchers with information of past developments and future trends in this area. The result shows that CO_2 is one of the most studied GHG emissions in calculating marginal abatement costs and some countries/regions have not received much attention from researchers in assessing emission reductions. Finally, the MACC bottom-up methodology focuses on the application of the engineering model method and the distance function method is a favorite in the application of the top-down method. Furthermore, this study also highlights possible research opportunities, which may lead to more successful and impactful results in future MACC studies.

INTRODUCTION

Over time, climate change has put a number of pressures on people's lives and in particular on the environment, leading to global warming (Grigoroudis et al. 2016, Gu & Wang 2018, Sununta et al. 2019). Governments around the world have made commitments to avoid serious climate change, by taking measures to reduce emissions of greenhouse gases (GHG) to stabilize the global average temperature rise to "well below" two degrees Celsius compared to temperature levels of the pre-industrial age (Talaei et al. 2020, UNFCCC 2015). To achieve this global target, an acceptable abatement plan must be developed to greatly reduce the total emission reduction costs. Estimating GHG abatement costs can help the government and firms make reasonable policy decisions. One tool for examining the relationship between environmental policy and technical change is the marginal abatement cost curve (MACC or MAC curve) (Ibrahim & Kennedy 2016, Kesicki 2013). Marginal abatement cost curves are a useful tool, which has been developed a lot over the last 20 years, for evaluating CO_2 mitigations options and comparing different abatement measures, and representing information on abatement costs of specific technology and potentials for a set of mitigation measures (Chen 2018, Oliveira et al. 2015). Abatement cost is one of the fundamental criteria which provide policymakers with intuitive cognition of economic perspective (Teng et al. 2014). A MAC curve plots the shadow price corresponding to an emission constraint of increasing severity against the quantity abated and that cost curves are unique for each country and show the relationship between reduction in emissions and the marginal cost per unit of abatement (Juntueng et al. 2020, Zhang et al. 2017). A positive MAC value indicates that there is a cost to reducing emissions relative to the baseline, while a negative MAC value indicates a benefit in reducing GHG emissions relative to the baseline (Eory et al. 2013).

For global and country-specific scenarios, several studies have applied this tool for technology assessment and for comparing projects and opportunities for mitigation of GHG emissions (Lee & Wang 2019, Vogt-Schilb & Hallegatte 2011). Several applications of the MAC curve are found in the power sector, building, agriculture, shipping, residence, transport, and policy-making (Jones 2014, Luu et al. 2018). Its growing popularity is mainly due to its simplified representation of the complex relationship between emissions abatement efforts and the marginal cost of cutting one unit of CO_2 emissions (Sjostrand et al. 2019).

CONCEPT OF MARGINAL ABATEMENT COST

The implication of estimating environmental costs per unit of product is to estimate the amount of MAC charged to each unit of product, meaning how much is the contribution (share) of one unit of product in reducing the amount of waste discharged into the environment (et al. 2016). Marginal cost is a decrease or increase in the total cost paid due to the addition or subtraction of one additional unit of product. The MAC is constructed to show the quantity of greenhouse gas (GHG) that can be abated with their comparable costs relative to a reference technology. Abatement cost calculation has been based on comparisons of different technology costs and emissions relative to BAU or baseline/reference model that is stated in the following general formula:

$$MAC = \frac{(Cost\ of\ GHG\ Mitigation\ Option - Cost\ of\ GHG\ BAU\ Model)}{(GHG\ Emission\ from\ BAU\ Model - GHG\ Emission\ from\ Mitigation\ Option)}$$

where,

$$Cost\ of\ GHG\ Mitigation\ Option = \sum_{i=1}^{n} (Capex_i + Opex_i)/(1 + funding\ cost)^{year\ of\ depreciation}$$

MAC uses the sum of capital expenditure (Capex) and operational expenditure (Opex) for each energy end-use were estimated based on the technology cost (González-Mahecha et al. 2019). Once the technical mitigation potential and marginal abatement cost have been quantified for each measure, the measures are then grouped and ranked based on their cost-effectiveness. The mitigation measures are ranked from left to right along the x-axis from the lowest to the highest MAC and the y-axis shows the cost per tonne of CO_2 equivalent (tCO_2e) reduced (Selvakkumaran & Limmeechokchai 2017). The key principle is that technologies should only be used when the abatement costs are lower than those of other mitigation strategies. The curves can be viewed as guidance for firms, entrepreneurs, and government officials contingent upon the degree of accumulation of the amount of GHGs abated by each measure represented. It also unmistakably shows which is the following, more costly technology that should be applied to obtain an extra abatement.

CLASSIFICATION OF MACC METHOD

At the national, company, or level of society, the MACC can be developed using three methods: top-down/non-model-derived, bottom-up/model-derived, and hybrid (Tang et al. 2020). Each method has different advantages and disadvantages that may address the various concerns. For example, a high degree of technological detail becomes the major advantage of the bottom-up method, while it has a disadvantage which does not capture system-wide interactions, behavioral aspects are neglected, the baselines may be inconsistent and reduction potential double counted (Delarue et al. 2010, Kesicki & Strachan 2011, Wächter 2013). The top-down approach for the sectorial level could be used to assess how markets address exogenous pressures, including an undertaken or pending policy action and its consequences for a system (Levihn et al. 2014), but are often required sophisticated financial modeling used to predict the emissions and costs of different policies so that they constitute a compromise and do not correspond to empirical relationships (Huang et al. 2016, Levihn et al. 2014). The hybrid method unites the strength characteristics of the top-down and bottom-up methods, however, due to high data requirements and the complexity of the quantification process, the hybrid approach has not been widely used (Jiang et al. 2020, Tanatvanit et al. 2004).

Bottom-up Method

The bottom-up method estimates the MACC according to different policies and technology for mitigation (Bockel & Sutter 2012). This approach is focused on the choice of energy and technology, and cannot simulate the impact of energy price changes, factor prices, and other intermediate input costs; the production function model focuses on estimating the historical MAC, while it cannot simulate the policy change (Baker & Barron 2013, Tang et al. 2020). Fig. 1 displays an example graph of MACC, whereas top-down models often use piecewise-smooth functions and bottom-up models use a step function (Kiuila & Rutherford 2013). Many studies have investigated CO_2 emissions abatement strategies using the bottom-up approach with different applications and results, especially for countries and sectors level (Fan et al. 2017).

Top-down Method

Contrary to the bottom-up approach, which emphasizes the comprehensive technology portfolio, the top-down approach concentrates on evaluating the cost of potential opportunities for a certain reduction objective, while disrupting production processes, responding to market behavior, obtaining hidden costs for producers and customers, and catching the price rebound effects (Huang et al. 2016). Table 1 shows the differences between the two methods. Furthermore, the top-down model can be divided into the microeconomic supply model and the Computable General Equilibrium (CGE) model which measures the impact of reductions in prices and general market behavior (Löffler & Hecking, 2016). The distance function is one of the micro-economic models that are widely used for constructing a production feasible set (or production frontier) subject to technical and economic conditions, to derive the shadow prices (or opportunity cost) of abating an additional unit of undesirable output in many

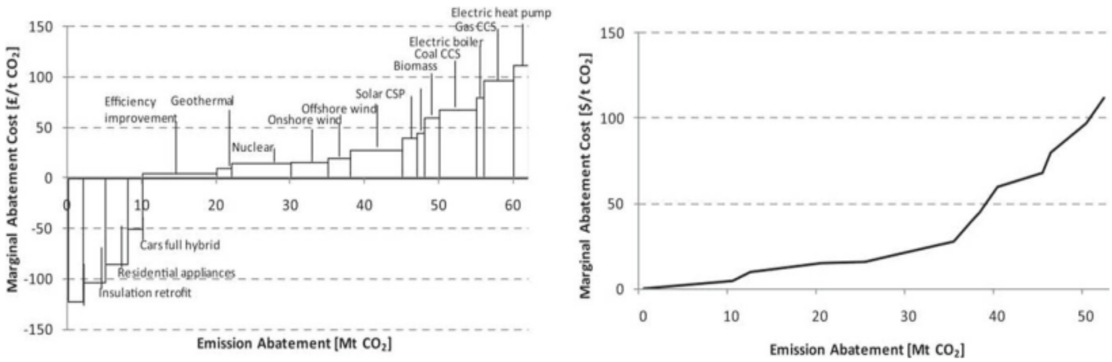

Fig. 1: Different MAC Curves using bottom-up method (left) and top-down method (right) (Kesicki & Ekins, 2012).

Table 1: Main differences in Bottom-up and Top-down methods.

Bottom-up Method	Top-down Method
Developed based on expert (scientific) judgment	Developed based on system modeling (MACC for energy system)
Presenting details of each mitigation option/technology	Modeling is considering energy supply and demand system
Not considering interactions between mitigation options, or supply & demand systems	Accommodating the development of mitigation options in the form of scenarios

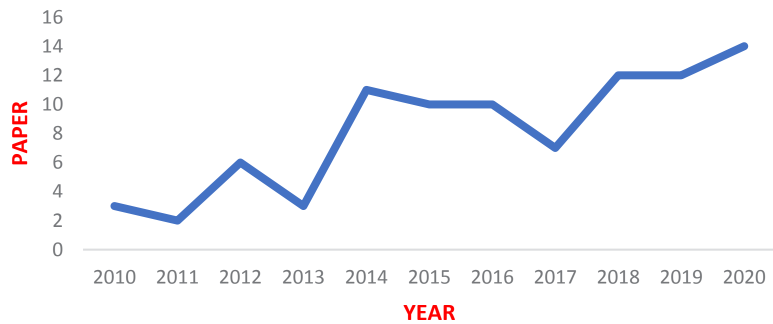

Fig. 2: Trends in MACC's research publications.

applications and locations (Chen 2015, Sala-Garrido et al. 2021).

MACC'S SCOPE OF APPLICATIONS

]MACC has since become increasingly widely used in particular regions, countries, industries, and/or pollutants (Eory et al. 2018). The timeframe, journal types, and keywords were identified for the literature collection framework. Literature published from 2010 to 2020 was the subject of attention. Fig. 2 shows the increasing number of MACC research publications in international journals. This study concentrates on central articles relevant to specific MACC using the top-down and bottom-up methods totaling 83 papers (Fig. 3) and explores the applicability of the first and second approaches through three analytic dimensions including GHG emission type, research objects, and modeling methodologies which will be further elaborated as follow.

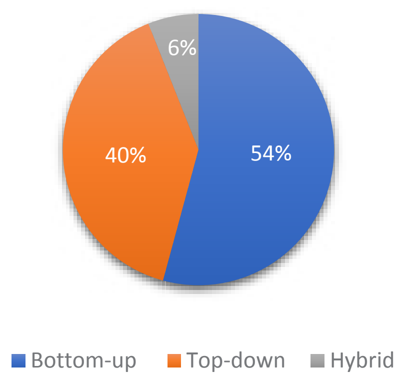

Fig. 3: MACC's research publications by methods.

Applications on GHG Emissions

Among the studies on the top-down and bottom-up methods, CO_2 is one of the most studied GHG emissions in calculating marginal abatement costs because it is the primary GHG that accounts for around three-quarters of emissions and is becoming an increasingly global focus. Many researchers quantified the CO_2 MAC in various sectors and used different modeling methodologies to develop MACCs. The MACC also enables a better understanding of the reduction potential for non-CO_2 sources and the incorporation in the economic modeling of non-CO_2 GHGs reductions, such as CH_4 or N_2O (Verma et al. 2015). For non-CO_2 gas, a single optimized MACC technology-specific was developed by using boiler-level data as input for an integer linear program, minimizing system-wide cost control by ensuring an optimum distribution of NO_x controls over the modeled detailed boiler specification (Vijay et al. 2010).

Applications on Countries and Sectors

Any research related to calculating the marginal cost of emission abatement always requires a research object in the form of a sector or country. The following figure shows the total number of sectors and countries used as research objects in developing MACC from 2010 to 2020 (Fig. 4 and Fig. 5). The MAC calculation of a country or province is the most studied (20.5%), followed by the residence and building sector (14.5%), and power generation (13.3%). For example, the CO_2, SO_2, and NO_x MACs are estimated from 2006–2014 through the shadow price framework for 105 Chinese urban areas (Ji & Zhou 2020). In European territory, the evaluation of planned development of the South/Central Stockholm District Heating network and potential mitigation options was analyzed by exploring the dynamic, path-dependent aspects (Levihn et al. 2014). Other researchers have also tried to evaluate and develop MACC in multi-sectors (12.1%) using top-down and bottom-up methods. MACC has also been applied to approximate global emission abatement, although the publication is running at a slow pace (3.6%).

In addition, other sectors, such as transportation, agriculture, oil, and infrastructure are starting to be researched on abating emissions to meet national emission reduction targets. The agricultural sector is the world's second-largest emitter, after the energy sector (which includes emissions from power generation and transport). Scientists have also evaluated emission reductions in certain sectors that have

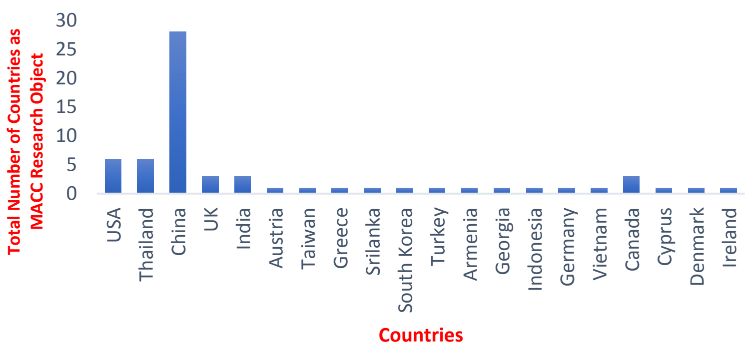

Fig. 4: MACC's Research Publications by country.

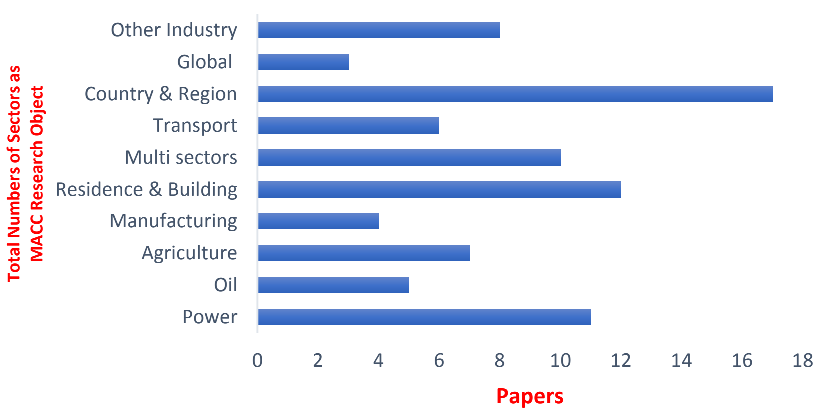

Fig. 5: MACC's research publications by sector.

not been described in the previous points, such as maritime shipping or livestock (Schwartz et al. 2020).

Applications with MACC Methodologies

When scientists use top-up or bottom-up methods, the development of modeling scenarios should be further translated into a modeling methodology (Hasler et al. 2019, Mosnier et al. 2019). Assumptions and costs of the reduction measures are set up to generate marginal technologies costs and their potential to reduce GHG emissions (Marinoni & Grieken 2015). Ibrahim & Kennedy's (2016) work is an example of bottom-up financial accounting methods. The technologies considered in their study are analyzed based on a Net Present Value (NPV) methodology that considers the prices of electricity, fuel, and energy in each city. There are still several research publications that include how the application of the NPV method for generating the MACC and this method is increasingly popular for private investors because of its simplicity in calculations and its capability to classify cost-effective measures.

The bottom-up engineering models approach has a riches of detailed energy system technical specifications and is better positioned to optimize the portfolio of options and minimize system cost. MARKAL studies that analyze MAC using typical bottom-up modeling are commonly used. In the transportation and residential sector, the MARKAL model was used to find the cost and potential abatement in the UK to overcome the shortcomings of existing approaches. Low Emission Analysis Platform (LEAP) is another energy model used to assess to evaluate the potential long-term potential and marginal costs of cogenerated electricity in the oil sands sector by means of a new combined market penetration model and bottom-up energy system modeling framework.

The CUECost model was implemented to create supply curves for pollution abatement using boiler-level data that explicitly accounts for technology cost and performance in the USA power sector (Vijay et al. 2010). The TIMES-GEECO model is an abbreviation of TIME's model generator for "TIMES Gauteng Energy and Emission Cost Optimization". For the Korean power sector, The Model for Energy Transition and Emission Reduction (METER), is used to derive the MACCs because it conveys very well the features of Korea's energy system than any other model and is flexible enough to enable us to perform different analyses (Ahn & Jeon 2019). Mitigation measures in the Agriculture, Forestry and Other Land Use (AFOLU) sector used the AFOLU bottom-up (AFOLUB) model to estimate GHG emissions.

Top-down methods can be further divided into the distance function method and the CGE model (Wang et al. 2018). Numerous scholars prefer the distance function approach, which leads to several relevant studies. In particular, the measurement using the distance function can be constructed by using the parametric Stochastic Frontier Analysis (SFA) method or the non-parametric Data Envelopment Analysis (DEA) method. Parametric DDF was also used to propose a new method to estimate CO_2 mitigation costs for 46 firms in the USA (Wang et al. 2018). For the chemicals industry, a MACC is created for energy-saving measures in Germany, quantifying the uncertainties in the results and identifying key input parameters. An example of a Non-parametric DDF was implemented to determine what factors will affect a change in the marginal abatement cost on allocating the burden of the emissions reduction for 30 provinces in China. Although the top-down method with DDF has experienced growth in research publications over the last 5 years, several studies have also accommodated the creation of MACC with the CGE model.

SUMMARY AND RESEARCH OPPORTUNITIES

By consolidating the previous MACC research, several things have been the focus of previous MACC research (Table 2). First, among all GHG emissions, researchers only consider the CO_2 emissions (82.89%), which are the main emissions from the industry and becoming a global concern. Second, some countries/regions have not received much attention from researchers in assessing emission reductions and identifying specific technologies used. The final summary is the MACC bottom-up methodology focuses on the application of the engineering model method (46.05%) and the distance function method (34.21%) is a favorite in the application of the top-down method.

Table 2: Summary of emission, research object, and methodology in MACC researches.

	Emission Scope			Research Object		Methodology			
	CO_2	Non-CO_2	Mixed	Industry/Firm	Country/ Region	Finance-Accounting	Engineering Model	Distance Function	CGE
Count	63	9	4	64	12	13	35	26	2
%	82.89	11.84	5.26	84.21	15.79	17.11	46.05	34.21	2.63

Based on summarizing part above, these are the following trends and possible research opportunities in MACC generation using the top-down and bottom-up methods:

(i) Scientists have focused a lot on the residence, building, power, transport, or agriculture sector in building MACC (Taylor 2012). There are still other sectors that produce GHG emissions, but further research is needed, for example, the palm oil sector is one of the plantation commodities that is much needed by the global industrial sector.

(ii) Current literature works are that the greater part of the research on the MACC of CO_2 only focused on regions and industries while few studies take a worldwide viewpoint. The MAC on GHG emissions from a global perspective needs and must be studied to obtain world environment sustainability (Akimoto et al. 2014, Hanaoka & Kainuma 2012).

(iii) Even though China is the largest GHG emitter country, there is still a need for a more country-specific MACC analysis, especially for developing countries, such as India, Indonesia, or African countries (Gore & Annachhatre 2017). Extension to developing countries would bring greater challenges to MAC research.

(iv) Both top-down and bottom-up methods have been widely applied with a variety of modeling systems and have seen a drastic increase in MACC research publications. The above models can be improved in all areas, such as developing abatement option-specific information on the complexities that are associated with the implementation.

(v) Low-cost mitigation solutions sound appealing, but there is reason to believe they are not the simplest to apply and policymakers are led to believe that the cheapest technology options are always the best options to realize, the reality proved to be different, however (Chappin et al. 2020). There is an opportunity to combine MACC with other decision support system tools e.g., Multi-Criteria Decision Analysis (MCDA) as a complementary tool alongside MAC curves.

CONCLUSION

This paper provides a review of MACC applications from its methodologies point of view, in particular top-down and bottom-up methods. The focus of this study is on central international articles and the top-down and bottom-up MACC method with a total of 83 papers. This paper also looks at three analytical dimensions, including GHG emissions type, sectors and countries as research objects, and modeling methodologies, for the applicability of those three approaches. MACCs are powerful instruments for understanding environmental policy and technological changes. When looking at the various ways that the MAC curve can impact different technologies, one can gain insights that can inform technology policy and emission policies. Furthermore, this study highlights the possible research opportunity, which may lead to more successful and interesting results for future MAC studies.

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