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Industrial low carbon futures: A regional marginal abatement cost curve for Sao Paulo, Brazil

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ABSTRACT

Sub-national and regional greenhouse gas (GHG) mitigation policies are being stimulated by the Paris Agreement. Several low carbon studies have been conducted for important emitters such as California State in the US and Chinese provinces. At the same time, carbon mitigation studies have focused on the industrial sector, especially in developing countries. In comparison to the national scenario, the Sao Paulo state in Brazil shows a distinct emission profile. The industry in Sao Paulo is responsible for 14.7% of the total emissions, and this share increases to 31.5% considering energy indirect emissions. Therefore, Sao Paulo mitigation efforts depend on industry's leadership such as in other parts of the world. The present study has evaluated the Sao Paulo state's industry mitigation potential between 2014 and 2030 based on a Marginal Abatement Cost (MAC) curve. In contrast to previous MAC studies, the MAC-SP study has also considered cement related emissions released outside its jurisdictions but that are driven by industrial choices within its boundary. Nine out of seventeen technologies show a negative MAC value, and energy efficiency technologies yield the lowest cost with a weighted average value of -\$122/metric ton of CO_2. Considering only the territorial based approach, the Sao Paulo state's Industry would avoid 78.4 million metric ton of CO_2 until 2030. Although emissions under Sao Paulo's responsibility increase 27%, if the consumption-based approach is adopted, the assessed mitigation potential enhances 83% and entails US\$ 2.3 billion savings until 2030. In conclusion, the mitigation potential for São Paulo state's industry is sizeable and consumption-based strategies are worthwhile, especially when regional policies are considered. Results can assist in formulating climate change policies and innovative incentive mechanisms to maximize the regional mitigation potential.

1. Introduction

The Cancun agreement (2010) has set the 2 °C limit on global warming, and the Paris agreement (2015) has enabled an emission mitigation strategy based on regional, national, and sub-national policies (Bodansky et al., 2016). This means that different policy instruments in distinct jurisdictions may be connected by reciprocal recognition and crediting for compliance. The advantage of such mutual initiatives is that they facilitate the emergence of least cost mitigation options. Several sub-national jurisdictions around the world have set emission reduction targets.

In North America, twenty states in the USA and the District of Columbia have set 2020 and longer-term goals. In California, the Global Warming Solutions Act (AB32), which was enacted in 2006, has determined that emissions in 2020 should be equal to emissions in 1990 (Morrison et al., 2015). As a result, several models have been run to evaluate the deployment of alternative low carbon scenarios to achieve the mitigation goals in California. A recent assessment has evaluated nine different energy models that sought medium and long-term greenhouse gas mitigation goals for the State of California (Morrison et al., 2015). Results show that, compared to 1990 emissions, emission reductions in 2030 are between 8% and 46%.

In China, seven sub-national emission trading schemes (ETS) have been launched (Xing et al., 2017). China has established a carbon intensity reduction target of 18% by 2020, considering 2015, and there was a previous goal to reduce carbon intensity by 40–45% in 2020, considering emission levels in 2005 (Xing et al.,

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2017). The experience with such regional ETS will be fundamental to establish a nationwide market and meet the national targets. Seven emission-intensive industries, including papermaking, electricity generation, metallurgy, non-ferrous metals, building materials, the chemical industry, and the aviation service industry will be targeted by the future Chinese ETS scheme, which denotes the prominence of industrial emissions in the national GHG budget. Another regional study on China's cement industry has shown that ancillary environmental benefits, such as air pollution reduction and air quality improvement, can be achieved by regional climate policies (Yang et al., 2013). Besides economic advantages, the regional focus also draws attention to regional pollution benefits.

The steel industry, which is another major source of CO_2 emission in China, has been assessed by the Long-range Energy Alternative Planning (LEAP) software (Wang et al., 2007). The average cost of CO_2 mitigation in 2015 and the cumulative emission reductions in 2030 were respectively $57 per metric ton of CO_2 (tCO_2) and 142 million (M) tCO_2 (Wang et al., 2007). The study has concluded that it is possible to reduce the CO_2 emission intensity from the Chinese steel industry by 33–41% in 2020, considering emissions in 2000. To a great extent, the growth in industrial energy use has occurred in developing and emerging economies (Selvakkumaran et al., 2014). In Thailand, the industrial sector, which consumed 20% of the country's energy in 2010, was responsible for 37% of the total emissions (Selvakkumaran et al., 2014). An assessment of the Thai industrial sector has demonstrated that it is possible to mitigate 19.5% of the emissions between 2010 and 2050 (Selvakkumaran et al., 2014). Similarly to China and Thailand, and considering differences in scale, industry related emissions are also relevant in Brazil, especially at the regional level.

In 2009, the Sao Paulo State government established its Climate Change State Policy (Law 13.798). According to such Law, emissions in 2020 should be 20% below the 2005 emission level (São Paulo, 2009). In 2015, the Brazilian Nationally-Determined Contribution (NDC) established a reduction pledge of 37% of its total domestic emissions in 2025 and an additional pledge of 43% in 2030, both based on 2005 Greenhouse gases (GHG) emissions (Brasil, 2015).

Assessments of sub-national emission mitigation efforts are useful because they target the most important emission sources of the region and promote a closer dialogue with local stakeholders and local ancillary benefits such as pollution reduction and political climate leadership. For instance, the most significative emission sources in Sao Paulo State differ from the ones at the national level. Energy related activities in Brazil are not the most significant sources of GHG emissions because most emissions come from land use change (Borba et al., 2012). About 60% of the emissions in Brazil in 2005 were due to land use, land use change and forestry; conversely, in Sao Paulo State, 57.2% of the emissions were related to energy conversion (CETESB, 2011). The situation in Sao Paulo State is comparable to California and the industrialized Chinese Provinces, in which energy related emissions stand out.

In 2005, GHG emissions in Sao Paulo State totaled 140 $MtCO_2$, and the industry was responsible for 14.7% of the total (CETESB, 2011). However, the industry inventory comprises only process-based emissions even though part of energy conversion emissions are due to industrial activities. The allocation of such emissions to the industry enhances the significance of the industry as a player in the decarbonization quest. Worldwide, one third of all energy consumption and 36% of CO_2 emissions are related to industrial activities (Selvakkumaran et al., 2014). Considering process-based emissions plus direct and indirect energy emissions, iron and steel production was responsible for 4.1% of the worldwide emissions in 2000 (Wang et al., 2007). Likewise, if a share of emissions inventoried for the energy sector is allocated to the industry, the industry in Sao Paulo would be responsible for 31.5% of the emissions in 2005. Therefore, assessing alternatives available to the industry to mitigate GHG emissions is relevant in terms of the current regulatory framework.

For policy makers it is important that economic performance metrics are presented in parallel with the proposed GHG mitigation pathways (Morrison et al., 2015). The relevance of cost effectiveness assessments stands out when the industrial sector is at stake.

The goal of this study was presenting the results of a recent MAC curve for the industry of Sao Paulo (MAC-SP) between 2014 and 2030 and comparing its results to similar studies in other jurisdictions. A set of cleaner production alternatives, including material and fuels efficiency and its substitution, were considered for the industrial sectors responsible for most of the CO_2 emissions. We present a brief explanation about the MAC approach and a review of other MAC studies that have focused on industrial GHG emissions. Next, we present a brief description of MAC-SP methods and its results. Finally, we compare the results of MAC-SP with other regional assessments, and MAC studies targeting the industry and provide some suggestions for future regional MAC studies targeting the industry.

2. Marginal abatement cost curve

Marginal abatement cost (MAC) curves can inform government officials and companies on the possibilities to attain carbon emission reduction targets (Isacs et al., 2016), becoming an important assessment tool for decision makers. Besides the production of a possible carbon mitigation scenario, the methodology determines the average costs of each mitigation technology. MAC curves determine the least cost options to attain a desired CO_2 mitigation target (Tomaschek, 2015). Although the absolute costs of each alternative is not the most relevant outcome of a MAC curve, it is especially useful for ranking the technologies in a specific sector (Huang et al., 2016). The approach is widely used in climate policy studies, including analyses targeting the industrial sector.

2.1. Theoretical basis

The MAC curve adopts a static approach, in which the MAC of each technology was obtained considering the difference between a reference scenario and a low carbon scenario to costs and emissions (Tomaschek, 2015).

The reference scenario is the business-as-usual case, in which GHG mitigation actions are spontaneous. The low carbon scenario considers the active introduction of technologies or measures to reduce GHG emissions. Resulting low carbon emissions should be necessarily under the reference emissions, however, technology costs in the low carbon scenario may be higher (positive MAC) or lower (negative MAC) than in the reference scenario.

The costs of both scenarios are composed by capital expenditures (CAPEX), fixed and variable operational expenditures (OPEX). Although energy costs are part of variable OPEX, they were analyzed independently because energy (fossil fuel and electricity) price forecasts affect annual costs, and therefore, the final MAC values. The discount rate is another key parameter in the MAC approach, because it is responsible for levelizing CAPEX values. The higher the discount rate is, the higher is the annual cost to pay back the investment over the technology's lifetime.

MAC Results are used to rank the technologies according to the average cost of one tCO_2 avoided emissions. One of the methods available to construct MAC curves rely on expert opinion which is used to calculate the cost and the potential of individual technologies and produce a graph ordering the alternatives from least to highest cost (Almihoub et al., 2013).

2.2. Previous MAC for the industry

Several MAC studies are intrinsically applied to the industrial sector, especially in developing countries. Indeed, industry's energy demand in developing countries increases but remains stagnant in Organisation for Economic Co-operation and Development (OECD) countries (Selvakkumaran et al., 2014). Studies addressing opportunities for a low carbon industry are particularly appealing to China. The industrial sectors participating in the sub-national emission trading pilot project are: paper making, electricity generation, metallurgy, non-ferrous metals, building materials, the chemical industry, and the aviation service industry (Xing et al., 2017).

Some industrial sectors stand out because of their significant share in total GHG emissions, international exposure, similarity among its products and manufacturing processes, and emitters concentration, and accordingly, due to such criteria, steel is one of the most important sectors in China's industry (Wang et al., 2007).

In 2010, the steel sector in China emitted 1.25×10^9 tCO_2 (Mao et al., 2013). Besides emissions of GHG, steel production is responsible for emissions of air pollutants such as sulfur dioxide (SO_2), nitrogen oxides (NO_x), particulate matter (PM). Reductions in CO_2 emissions can be achieved easier than reductions in pollutant emissions, and many of such reductions imply in pollution reductions as well, which are not usually assessed (Mao et al., 2013). Nevertheless, end of pipe CO_2 control technologies, such as carbon capture and storage (CCS), increase emissions of local pollutants because the scheme demands additional energy that may be obtained from fossil fuels combustion. According to Mao et al. (2013), CCS and Phasing out outdated production capacity (POPC) were responsible for 61% and 22% of the total CO_2 emission abatement potential in the Chinese steel sector, the remainder was mitigated through other technical reduction measures.

Another MAC study has assessed several carbon mitigation technologies in the iron and steel industry in China. Due to difficulties in accessing Chinese data, the study has relied on international data to report the potential and the costs of each alternative. The study period was between 2010 and 2030, and the assessment has considered annual steel demand forecasts up to 2030. The bottom up based study has assessed fifteen energy-efficiency measures and five electricity efficiency measures. Out of which, fourteen energy efficiency measures and four electricity efficiency measures are considered cost effective. That is, the net present value of the benefits from energy savings minus the costs of those measures is positive. The cumulative mitigation potential of all measures over the 20-year period was 1205 $MtCO_2$ (Hasanbeigi et al., 2013).

A MAC study was applied to the industrial energy sector in Thailand to evaluate emission tax as a key driver of GHG mitigation and the impact of mitigation in the energy security of the industry. Nine industrial sectors, including food and beverage, textiles, wood and wood works, pulp and paper, chemical and petrochemical, nonmetallic sector, steel, fabricated metal, and other sectors, were evaluated and results indicate a 20% mitigation potential in 2050 with positive energy security impacts. Technologies comprise high energy efficiency and new technologies and the assessment differentiates between electric devices and heating needs. Combined heat and power (CHP) is also considered by the assessment. However, the study has not considered CCS so that all assessed technologies also imply in significant energy consumption reductions. Three different MAC curves considering different periods are presented. New technologies, such as fossil fuel heaters and electric devices, are responsible for 60% of the total mitigation potential, whereas high efficiency technologies and CHP are responsible for 30% and 10%, respectively (Selvakkumaran et al., 2014).

3. Methods: MAC-SP approach

About seventeen options to curb GHG emissions have been evaluated in the MAC-SP study, which has received input from experts and stakeholders representing the industry. The MAC-SP study has relied on distinct approaches to develop future emission scenarios for each sector.

Scenarios in the MAC-SP study comprise the period between 2014 and 2030, considering 2013 economic values. The study encloses the following industrial sectors: Lime, Steel mills, Chemicals, and Cement manufacturing. Carbon mitigation options have considered both process based and energy based GHG emissions.

According to the 2005 inventory (CETESB, 2011), 95% of the industrial emissions in the State of Sao Paulo were released by Lime, Metallurgy, Chemicals, and Cement manufacturing. The assessment has focused on these four sectors. The analysis comprises the period between 2014 and 2030. In 2014, estimated emissions from these sectors were 21.4 $MtCO_2e$, including energy related emissions. Baseline emissions over the analyzed period were determined based on sectoral throughput forecasts. Each sector has been evaluated separately by an expert. Fig. 1 shows the evolution of the production for each sector.

The cement sector production grows faster than the other sectors. Although there are both conservative and optimistic estimates (range from 3% to 8% per year), 5% per year growth rate has been adopted according to National Cement Industry Syndicate (Pacca et al., 2017).

Steel mills production has been based on historic data, which shows a correlation between steel sector and the Brazilian Gross Domestic Product (GDP). A rate equal to 1.5 times the GDP growth was adopted to forecast steel mills production until 2030 (Pacca et al., 2017).

The chemical sector also grows according to the Brazilian GDP estimated by the São Paulo state's industry federation (FIESP), with 3.7% per year. However, the average annual growth along the period is 1%, because there is no expected expansion until 2030 of the installed capacity available in 2013. Each chemical plant output increases until it reaches the maximum installed capacity (Pacca et al., 2017).

Unlike the other sectors, the lime sector's production slightly decreases (0.8% annually). That evolution occurs because the quality of the limestone reserves in São Paulo State is inferior than the quality in other states. Moreover, it is expected that mortar

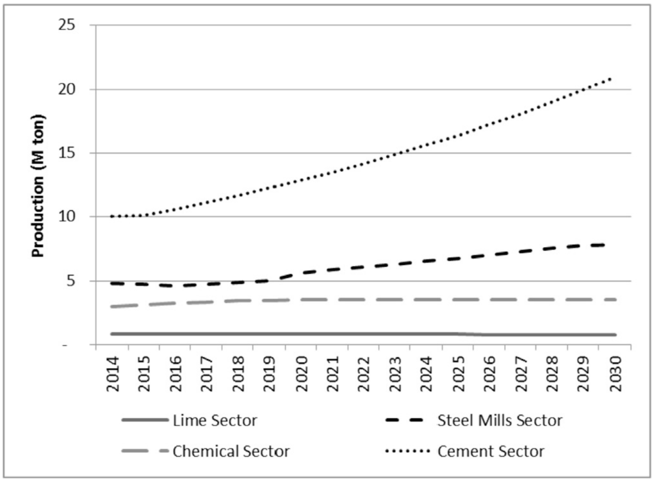

Fig. 1. Production growth by industrial sector 2014–2030.
Source: Pacca et al. (2017).

Table 1
Assumptions concerning the technologies assessed by the MAC-SP study.

Sector	Mitigation category	Technology	Economic Values about reference scenario			Mitigation about reference scenario
			Costs		Revenue	
			CAPEX	OPEX		
Chemical	Power conservation and generation	LED lamps	668 (US$/MWh)	−0.05 (US$/MWh)	none	36.6% power saving
		Efficient electric motors	6 (US$/MWh)	0 (US$/MWh)	none	11.7% power saving
		Natural gas Cogeneration	9.92 (US$/GJ)	0.31 (US$/GJ)	[a]	Generation of 105.4 kWh/GJ natural gas
	Fossil fuel substitution	Substitution of woodfuel for natural gas	5.21 (US$/GJ)	−0.27 (US$/GJ)	none	Reduction of 55.8 $kgCO_2$/GJ natural gas displaced
		Substitution of woodfuel for fueloil	5.21 (US$/GJ)	−0.27 (US$/GJ)	none	Reduction of 76.6 $kgCO_2$/GJ fueloil displaced
	Chemical processes	Ammonia	3.9 (10^6US$/unit)	0.2 (10^6US$/year)	none	Reduction of 24.9 $kgCO_2$/t ammonia
		Nitric Acid	3.1 (10^6US$/unit)	0.4 (10^6US$/year)	none	Reduction of 196.1 $kgCO_2$eq./t nitric acid
		Bioethene	132.0 (10^6US$/unit)	−3.0 (10^6US$/year)	415 (US$/t ethene)	Reduction of 23 $kgCO_2$/t vinyl chloride and 863 $kgCO_2$/t ethene oxide
Steel Mills	Power conservation	Consteel System (preheating and continuous feeding)	10 (US$/t steel)	0 (US$/t steel)	none	9.9% power saving
		Direct Current Transformer	11 (US$/t steel)	0 (US$/t steel)	none	5.3% power saving
	Steel processes	Top Gas Recycling Blast Furnace with MDEA	301 (US$/t steel)	6 (US$/t steel)	none	Reduction of 810$kgCO_2$/t steel (42% of total emission)
Lime	Fossil fuel substitution	Biomass Fueled Maerz lime Kiln	8.2 (10^6US$/kiln)	4.39 (US$/t quicklime) [b]	none	Reduction of 2.43 GJ PET Coke (240$kgCO_2$)/t quicklime
		Torrefied Biomass Fueled Maerz lime Kiln	11.2 (10^6US$/kiln)	5.32 (US$/t quicklime) [b]	none	Reduction of 2.68 GJ PET (266$kgCO_2$)/t quicklime
	Lime processes	Carbon Capture and Storage	28.80 (US$/t CO_2 captured)	71.35 (US$/t CO_2 captured)	none	80% of total CO_2 emission capture
Cement	Cement processes	Increasing of Filler in cement	0.104 (10^6US$/silo pair)	21.72 (US$/t Filler)	none	848 $kgCO_2$/t clinker displaced
	Fossil fuel substitution	Substitution of Woodpellets for PET Coke	[c]	[c]	none	99.8 $kgCO_2$/GJ PET Coke displaced
		Substitution of Refuse Derived Fuel (RDF) for PET Coke	[c]	[c]	none	99.8 $kgCO_2$/GJ PET Coke displaced

[a] The cogeneration revenue per MWh is variable according electricity prices along the period.
[b] For hydrated lime, the addiction of US$ 19.20 was considered as hydration cost per metric ton of lime.
[c] There is no additional cost, excepting energy prices, for fossil fuel displacement.
Source: Authors based on Pacca et al. (2017).

industrialization and the displacement of hydrated lime by other products will reduce its demand along the analyzed period (Pacca et al., 2017). The production of each sector was converted into GHG emissions applying the IPCC emission factors (IPCC, 1996), adopted by CETESB, the local environmental agency. In 2030, total emissions of these sectors for the baseline scenario equals to 30 $MtCO_2e$. Between 2014 and 2030, emissions from the lime sector decrease by 13%, emissions from steel mills increase by 51%, emissions from the chemical sector increase by 38%, and emissions from cement increase 43%. Cumulative emissions during the period are 442.5 $MtCO_2e$ (Pacca et al., 2017).

The low carbon emissions scenario comprises 17 technologies (Table 1) and not all technologies are implemented evenly during the period. Carbon capture and storage (CCS) and top gas recovery blast furnaces (TGRBF) are adopted only in 2025. Other technologies such as energy efficiency and fuel substitution in the chemical industry start in the beginning of the period and steadily evolve until 2030.

Technology penetration scenarios were established based on expert judgment. Although certain technologies, such as CCS, are not expected to be implemented before 2030, sector experts have evaluated its cost.

The MAC of each technology was determined through an incremental approach in which benefits and costs of the reference scenario and the low carbon emissions scenario technologies were considered, according to other MAC analysis such as Hasanbeigi et al. (2010, 2013) and Henriques et al. (2010). For some technologies, revenues and costs were assessed, whereas for other technologies, only costs were considered (Table 1). Equation (1) illustrates the approach adopted to determine the MAC.

Marginal Abatement Cost Calculation

$$MAC\ (\$/t\ CO_2) = \left(NAC_{low\ carbon} - NAC_{reference}\right) \Big/ \left(AE_{reference} - AE_{low\ carbon}\right) \tag{1}$$

Where:

MAC is the marginal abatement cost for each technology assessed.

NAC is the net annual cost of the technology in each scenario.

AE are the annual greenhouse gas emissions in each scenario.

A weighted average MAC value for each technology is determined based on the amount of avoided emissions for each year and an annual 8% discount rate that translates the stream of MAC over the period into a net present value (NPV) for each technology. The same 8% was adopted by the Brazil Low-Carbon Country Case Study (Gouvello, 2010). This value comes from the Long-Term Interest Rate (LTIR) applied by the National Development Bank (BNDES). The 2006–2016 LTIR average was 6.19% per year. (BNDES, 2016), the value of 8% assumes the incidence of spread and risk. All the monetary values in the study have been converted to dollar using an exchange rate of R$ 2.16/US$ 1. This was the average exchange rate between Brazilian reais and US dollars in 2013 (EPE, 2014). The exchange rate has been used when the national reference data for energy prices (as well firewood, power auction) and production inputs (as well as water) are retrieved in Brazilian currency.

Several technologies assessed save or displace fossil fuel-based electricity generation. Although the share of renewable energy in Brazil is high, a constant electricity emission factor of 0.59 tCO_2 per megawatt hour (MWh) has been adopted. This means that there is enough fossil fuel-based electricity to be displaced. In fact, in November 10, 2017 the average load of thermal power plants for the Southeastern Brazilian grid was responsible for 8.8 GW (ONS, 2017). Fuel emission factors provided by the IPCC were used, but emission factors for biomass conversion were zero because all consumed biomass is planted, which implies that biomass re growth uptakes the CO_2 emitted by bioenergy combustion.

Energy prices were determined based on price equivalences over the last 10 years between the price of Brent oil and the modeled energy carriers. In order to calculate future prices, we have relied on the projections of Brent oil from the Annual Energy Outlook (DOE/EIA, 2014). In the case of electricity prices, auction prices for new generation capacity in Brazil between 2013 and 2020 have been considered. Equation (2) presents the model that was used to calculate future electricity prices.

Auction based model for electricity price forecasts

$$P_n = 32.301\exp^{0.0983(\mathrm{n}-2003)} \tag{2}$$

Where P_n is the electricity price in year n.

Additional 24% in taxes, transmission, and distribution fees have been added to reflect industrial electricity consumer prices.

Table 1 shows cost assumptions and mitigation potential for each technology evaluated. These are incremental values, which denote low carbon scenario values subtracted from reference scenario values. Levelized CAPEX was added to OPEX and energy expenses to yield the NAC presented on Equation (1). Energy costs vary along the period.

4. Results

A MAC curve was assembled and the emission reduction potential was consolidated on a wedge graph.

4.1. Production based approach

According to the model, 78.4 $MtCO_2$ are mitigated over the analyzed period. This figure corresponds to 18% of the emissions in the period. Besides industrial process based emissions, the study also comprises energy conversion related emissions because energy supports industrial transformation and is subject to choices within the industrial sector. Notably, the mitigation potential and the economic advantages related to energy efficiency technologies are sizeable. The CO_2 mitigation potential pertaining to energy efficiency (EE) technologies is 23.7 $MtCO_2e$ emissions, whereas the potential of fuel substitution alternatives is 16.4 $MtCO_2$ emissions. Based on EE emission reductions and the emission factor adopted for the displaced electricity, the corresponding fossil fueled based installed capacity that is made available is 270 MW.

Among the assessed sectors, the chemical sector is responsible for 40% of the total emission reductions, out of which 95% is due to energy conversion emissions. The cement sector is responsible for 30% of the mitigation potential. The single technology with the highest mitigation potential (25%) is top gas recovery blast furnace with methyl diethanolamine (TGRBF-MDEA) for the steel mill sector. Regarding the steel mill sector assessment, considering phasing out the integrated steel mill in Sao Paulo State would add 104 $MtCO_2$ of emission reductions or 1.3 times the total mitigation potential of all technologies assessed.

The results of the MAC-SP (Fig. 2), demonstrate that not all industrial sectors are equally competitive and present the same mitigation potentials. Nine of the assessed options present a negative MAC. This corresponds to no regret options that in comparison to the baseline scenario yield GHG reductions allied to economic benefits. Most of such options are in the realm of energy efficiency, in which the chemical and steel mill sectors stand out. The weighted average of all assessed measures is -$29/$tCO_2$, whereas the weighted average of the energy efficiency technologies

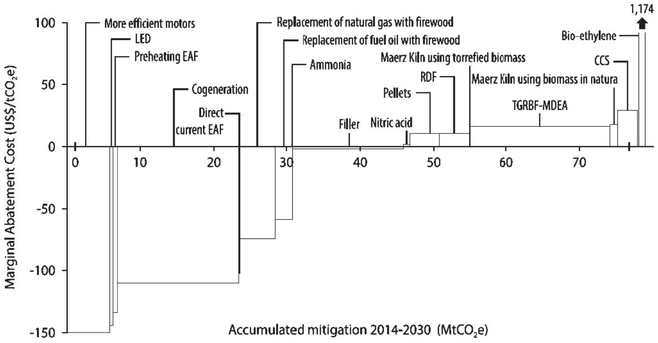

Fig. 2. MAC Curve for São Paulo's industrial sector.
Source: Pacca et al. (2017).

is -\$122/tCO$_2$.

It is noticed that the renewable fuel choice for fossil substitution plays a key role due to difference of energy prices. For example, although, in comparison to firewood, the use of ethanol shows some technological and environmental advantages, the displacement of natural gas and fuel oil yields positive MAC values \$390/tCO$_2$ and \$284/tCO$_2$, respectively.

The lowest MAC option relates to efficient electric motors in the chemical industry (US\$ −150/tCO$_2$). However, considering the global result, cogeneration is responsible for the largest economic benefit because of its large mitigation potential. The economic outcome related to the full potential of cogeneration along the assessed period equals to US\$ 1.8 billion.

The option that resulted in the highest MAC is part of the chemical sector as well, and entails ethanol based ethene production, which displaces emissions from fossil fuels based production of ethene oxide and vinyl chloride. The MAC for this alternative is \$1174/tCO$_2$, which is mainly affected by ethanol prices that are forecasted up to 2030. A sensitivity analysis demonstrates that ethanol prices should be 44% lower than the baseline forecast so that the MAC of the option approaches to zero. That is, this measure could be as profitable as petroleum based ethene if average ethanol prices are below \$30 per gigajoule (GJ). This would be possible if the industry produces its own ethanol so that taxes over the commercialization of ethanol are voided. Another possibility is reducing the bio-ethene MAC by rising its revenue and transferring additional costs to the consumer. In the main analysis, bio-ethene sales price is 30% above the petroleum-based ethane price.

The option with the second highest price was carbon capture and storage (CCS), which was considered for the lime sector. CCS is a popular technology in low carbon studies, although there are no studies or installed facilities for this technology in Brazil. In our study, CCS was responsible for 80% of emission reductions in the lime sector. No other alternative was envisioned to curb such emissions that arise from limestone calcination. The MAC for this alternative is US\$ 29/tCO$_2$ and its calculation has not included CO$_2$ transportation and storage because the experts involved in the assessment have considered that the industry was not responsible for these stages. Indeed, data limitation and the consideration of CCS mainly for power plants challenge a complete quantitative assessment of this technology, with few studies applied in the steel sector (Wang et al., 2007), and even less in the lime sector.

When cement manufacturing is at stake, adding filler shows attractive results because it represents 19% of study's global potential allied to a negative MAC. A low carbon study for the cement industry in Ukraine obtained a minimum value of \$4/tCO$_2$ for emission mitigation in a cement plant (Kajaste and Hurme, 2016). The same study considered a maximum 36.4% share of clinker substitution, value close to the one adopted in our study (40%).

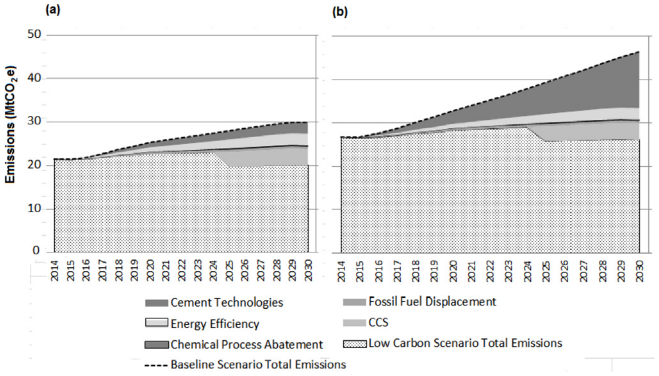

Fig. 3. Baseline scenario and avoided emissions by São Paulo's Industrial sector between 2014 and 2030; (a) territorial and (b) consumption-based accounting.
Source: Authors based on Pacca et al. (2017).

Technologies presenting the lowest MAC are related to energy conservation and the chemical sector. Although such measures are economically attractive they might need some legal support. For instance, electricity sales from natural gas cogeneration depend on appropriate regulations. The MAC for substitution of filler for clinker is roughly a neutral value, therefore, a minimal economic incentive might enable its substantial potential. To enable technologies relying on carbon storage, government support is required for: sites evaluation, pipelines and well deployment.

The mitigation potential of the cement industry enlarges under the consumption-based approach adopted by MAC-SP, which is described next.

4.2. Consumption based approach for the cement industry

Worldwide, high-income countries have imported GHG emissions incorporated in products principally from upper-middle-income countries (Victor et al., 2014). GHG assessments considering consumption related emissions are more meaningful than territorial emissions-based assessments, mainly when demand for inputs is expressive in the total product of a determined sector.

A supplementary assessment targeting the cement sector was carried out in which consumption-based emissions were considered. Such an approach has expanded the emission reduction potential beyond the territorial borders of Sao Paulo State, and has included some applications of cement such as mortar and concrete. In state cement consumption is 66% larger than its production, and São Paulo is an important cement consumer from other states. Besides that, there are no expectations that cement production in the state will increase, and part of the growth is based on grinding facilities that import clinker from elsewhere. Emissions from calcination take place in other states.

Three additional options were assessed considering consumption-based emissions. Such options target the dematerialization of cement consumption in the construction sector: increasing the use of industrialized mortar, increasing the use of ready mix concrete, and increasing the use of industrial concrete mixers. All measures aim to increase the efficiency of cement use. Because the amount of cement increases in such scenario, the other considered options (filler, RDF, and pellets) have their mitigation potential extended as well.

Results demonstrate that a 143.7 MtCO$_2$e emissions are mitigated, which accounts for additional 83% emission reductions in comparison to the territorial based assessment. According to such an approach, the cement sector stands out as the most relevant in terms of mitigation potential with 62% of the total emissions abatement, and filler becomes the most relevant option with 50.5 $MtCO_2$ avoided emissions (35% of the total). Considering the 20 proposed measures, US$3.2 billion would be saved up to 2030. Although the consumption based approach increases the responsibility of the state by 27% it enhances the mitigation capacity by 83%. Such an approach is beneficial to reduce industrial related GHG emissions. Fig. 3 presents the mitigation potential for each group of technologies assessed.

Considering the regional scope of MAC-SP, its mitigation potential is within the range of studies evaluating the mitigation potential in California, which was between 8 and 46% considering emissions in 1990. Regarding the approach adopted by MAC-SP, it was similar to other studies that focus on the largest industrial emitters and combine process and direct plus indirect energy emissions. The inclusion of a consumer-based emissions accounting perspective was not identified in previous published MAC. Although such an approach increases baseline emissions, it renders a much larger emission mitigation potential than MAC based on territorial emissions. The approach is relevant for industrial related MAC because similarly to energy efficiency alternatives, the industry can optimize the use of materials in their processes and products.

Although bottom up expert based MAC are limited, they provide a rank of alternatives to be considered by the industry. This effort was useful for promoting the MAC methodology for others cost-benefit analyses, as is the case, for example with water industrial pollution (Gunawardena et al., 2017).

5. Conclusion

The present paper presents a regional MAC for the industry. Although the mitigation potential varies according to each industrial segment, it has been shown that the GHG mitigation potential for the Sao Paulo state's industry (78.4 $MtCO_2$) is sizeable and entails US$ 2.3 billion savings until 2030. Total savings are mostly determined by energy efficiency related measures, particularly natural gas cogeneration in the chemical sector. When emissions, based on a consumption-based approach, were considered, the mitigation potential has increased to 143.7 $MtCO_2$. The incorporation of materials' indirect emissions due to cement consumption brings about greater mitigation potentials than assessments considering only direct territorial-based emissions. The results achieved can assist in formulating climate change policies and incentive mechanisms for establishing effective least cost mitigation technologies.

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