Low Carbon Study for São Paulo's Industrial Sector 2030

Summary Report

2 edition

Executive Summary

Government of the State of São Paulo

Secretariat of Infrastructure and Environment

CETESB – Environmental Agency of the State of São Paulo

IDB – Inter-American Development Bank

São Paulo, 2019

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Environmental Company of the State of São Paulo
Avenida Professor Frederico Hermann Jr., 345
Alto de Pinheiros CEP 05459-900 São Paulo SP
Phone: +55-11-3133-3000
https://www.cetesb.sp.gov.br

GOVERNO DO ESTADO DE SÃO PAULO

Governor João Doria

SECRETARIAT OF INFRASTRUCTURE AND ENVIRONMENT

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CETESB – Environmental Company of the State of São Paulo

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Director of Evaluation and Environmental Impact Domenico Tremaroli

Director of Engineering and Environmental Quality Carlos Roberto dos Santos

Technical data

Technical coordination
Sérgio Almeida Pacca

Executive coordination
Josilene Ticianelli Vannuzini Ferrer
Daniel Soler Huet - support

2nd Technical review
Sérgio Almeida Pacca

Authors
Sérgio Almeida Pacca
Jhonathan Fernandes Torres de Souza
Bruna Patrícia de Oliveira
Josilene Ticianelli Vannuzini Ferrer

Tecnical revision
Bruna Patrícia de Oliveira

Translation
Hilda Maria Lemos Pantoja Coelho

Graphic design and layout
Brainstorm Arte em Comunicação
Wilson Issao Shiguemoto

Photos
CETESB/BID

This report is a summary of the following studies:

Estudo de Baixo Carbono para a Indústria de Cal no Estado de São Paulo de 2014 a 2030
Authors:
José Milton de Freitas
René Vogelaar
Renato Vogelaar

Estudo de Baixo Carbono para a Indústria Siderúrgica no Estado de São Paulo de 2014 a 2030
Authors:
José Milton de Freitas
René Vogelaar
Renato Vogelaar

Estudo de Baixo Carbono para a Indústria Química no Estado de São Paulo de 2014 a 2030
Authors:
Obdúlio Diego Fanti
Roberto Strumpf
Jhonathan Fernandes Torres de Souza
Natália Kurimori

Estudo de Baixo Carbono para a Indústria de Cimento no Estado de São Paulo de 2014 a 2030
Authors:
Kátia Regina Garcia Punhagui
Lidiane Santana Oliveira
Jhonathan Fernandes Torres de Souza
Vanderley Moacyr John

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List of abbreviations and acronyms

ABIQUIM Associação Brasileira da Indústria Química (Brazilian Chemical Industry Association)

ABCP Associação Brasileira de Cimento Portland (Brazilian Association of Portland Cement)

AFOLU Agriculture, Forestry and Other Land Use

ANEEL Agência Nacional de Energia Elétrica (Brazilian Electricity Regulatory Agency)

APEC Asian-Pacific Economic Cooperation

BDI Associação Brasileira de Desenvolvimento Industrial (Brazilian Association of Industrial Development)

BECP Break Even Carbon Price

BEN Balanço Energético Nacional (National Energy Balance)

BNDES Banco Nacional de Desenvolvimento Econômico e Social (Brazilian Bank for Social and Economic Development)

BS Baseline Scenario

CAPEX Capital Expenditure

CCS Carbon Capture and Storage

CDM Clean Development Mechanism

CEPEA/ESALQ Centro de Estudos Avançados em Economia Aplicada da Escola Superior de Agricultura (Center of Advanced Studies in Applied Economics, "Luiz de Queiroz" Higher School of Agriculture)

CETESB Companhia Ambiental do Estado de Sao Paulo (Environmental Agency of the State of Sao Paulo)

CMN Conselho Monetário Nacional (National Monetary Council)

COP Conference of the Parties

CRF Capital Recovery Factor

EAF Electric Arc Furnace

EF Emission Factor or Factors

EGP Egyptian Pound

EIA Energy Information Administration

EOR Enhanced Oil Recovery

EPE Empresa de Pesquisa Energética (Energy Research Company)

ESMAP Energy Sector Management Assistance Program

FAT Fundo de Amparo ao Trabalhador (Workers' Assistance Fund)

FIESP Federação da Indústria do Estado de Sao Paulo (Federation of Industries of the State of Sao Paulo)

FO Fuel Oil

GDP Gross Domestic Product

GHG Greenhouse Gas

GWP Global Warming Potential

IABr Instituto do Aço Brasil (Brazilian Steel Institute)

ICMS Imposto Sobre Circulação de Mercadorias e Serviços (Value-Added Tax on Sales and Services)

IDB Inter-American Development Bank

INDC Intended Nationally Determined Contribution

IPCC Intergovernmental Panel on Climate Change

IRR Internal Rate of Return

ISS Imposto Sobre Serviço de Qualquer Natureza (Service Tax)

LCV	Lower Heating Value
LCS	Low Carbon Scenario
LED	Light Emitting Diode
LPG	Liquefied Petroleum Gas
LTIR	Long Term Interest Rate
MAC	Marginal Abatement Cost
MCT	Ministério da Ciência e Tecnologia (Brazilian Ministry of Science and Technology -currently MCTI)
MCTI	Ministério da Ciência, Tecnologia e Inovação (Brazilian Ministry of Science, Technology and Innovation)
MDEA	Methyldiethanolamine
MDIC	Ministério do Desenvolvimento, Indústria e Comércio Exterior (Brazilian Ministry of Development, Industry and Foreign Trade)
MME	Ministério de Minas e Energia (Brazilian Ministry of Mines and Energy)
NG	Natural Gas
NDC	Nationally Determined Contribution
OECD	Organization for Economic Cooperation and Development
OPEX	Operational Expenditure
p.a.	Per annum
PDD	Project Design Document
PDE	Plano Decenal de Expansao de Energia (Ten-Year Energy Expansion Plan)
PEMC	Política Estadual de Mudanças Climáticas (State Climate Change Policy)
RDF	Refuse-derived fuel
RG	Refinery Gas
SGT	Superintendência de Gestão Tarifária (Tariff Management Superintendence)
SNIC	Sindicato Nacional das Indústrias de Cimento (National Cement Industry Union)
SP	Sao Paulo State
TGRBF-MDEA	Top Gas Recycling Blast Furnace — Methyldiethanolamine
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
USP	University of Sao Paulo
WTI	West Texas Intermediate

List of chemical symbols and units

BOE	Barrel of oil equivalent
C_2H_4	Ethene/ethylene
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
Gg	Gigagram = 10^9 g
GJ	Gigajoule = 10^9 Joules
H_2	Hydrogen
HNO_3	Nitric acid
kg	Kilogram = 10^3 grams
kWh	Kilowatt-hour = $3{,}6 \times 10^6$ Joules
m^3	Cubic meter
Mt	Megaton
MWh	Megawatt-hour = $3{,}6 \times 10^9$ Joules
N_2	Nitrogen
N_2O	Nitrous oxide
NH_3	Ammonia
NO	Nitric oxide
ppm	Part per million
t	Ton
TOE	Ton of oil equivalent
TJ	Terajoule = 10^{12} Joules

Executive summary

In the State of Sao Paulo, considering the regulatory context, the State Climate Change Policy (PEMC) created by Law 13,798 of November 9, 2009 (SAO PAULO, 2009) establishes the State's commitment to reducing its greenhouse gas (GHG) emissions by 2020, based on 2005 levels (CETESB, 2013).

Sao Paulo's industrial sector stands out in the national scene in terms of relevance and the way environmental issues are addressed. The 1st Inventory of Anthropogenic Emissions of Direct and Indirect Greenhouse Gases of the State of Sao Paulo: Period 1990 to 2008 was completed in 2011. The inventory included emissions for industrial sectors and processes and use of products, energy, agriculture and livestock, land use, change in land and forest use, and solid waste and liquid effluents for the period 1990–2008. GHG emissions from the State of Sao Paulo were approximately 0.14 $GtCO_2e$ and industrial processes accounted for 14.7% in 2005 (CETESB, 2013). The industry is also a major energy consumer, accounting for 57.2% of the state's emissions in 2005, out of which 29.4% corresponded to energy consumption by the industrial sector (CETESB, 2013). Thus, this study evaluated alternatives through which the industrial sector can contribute to the achievement of the state's climate mitigation targets.

The "Low Carbon Study for Sao Paulo's Industrial Sector – 2014 to 2030" analyzes low carbon alternatives for the lime, steel, chemical and cement sectors. Unlike the inventories that separate emissions from industrial and energy processes, this study includes emissions from energy consumption by industry, since energy is essential for activities in this sector to occur, i.e., it is part of the production system. In fact, the choices recommended by the study may result in a significant mitigation potential as well as in economic advantages.

Future GHG emissions are the product of dynamic and complex systems determined by driving forces such as population growth, socioeconomic development and technological change, whose evolution is uncertain. The emission reduction alternatives contained in the study were analyzed from baseline and low carbon scenarios considering GHG emissions from processes and energy consumption and the evaluation of the costs associated with the mitigation alternatives.

The results show low cost alternatives that may entail substantial reductions without compromising the competitiveness of Sao Paulo's industrial sector. The scenarios contribute to identifying potential threats, assess organizational competencies, and exercise global thinking for developing strategic alliances and actions, enabling alternative analyzes. Therefore, it is not just about prospecting, but about building a possible future by helping the development of the desired changes for the future (WRIGHT, 2008 apud MENDONÇA, 2011).

Based on the scenarios, the study conducted an economic assessment of measures and technologies aimed to reduce GHG emissions, presenting the Marginal Abatement Costs (MAC) and the Break Even Carbon Price (BECP) of each opportunity. The scenarios in the present study were projected for the period 2014 2030 based on the year 2013, and constructed based on the analysis of historical data, information contained in publications of the analyzed sectors and information attributed by the authors. Actual historical data was assessed to update the industrial production up to 2018 (SNIC 2019; SÃO PAULO 2019; IABr 2019; IABr 2018; IABr 2016; IABr 2015) and expert projections were maintained thereafter. Emission reductions over the period analyzed for each technological option were consolidated in a Wedge Graph representing the mitigation potentials of each alternative.

Considering that this is a region that seeks to reduce emissions, it is observed that not always all sectors present productive systems with the same level of competitiveness or reduction potential. Therefore, it is essential to estimate the associated costs and the potential of the technologies for reduction targets to be achieved in a more economically attractive way. Nevertheless, considering all low carbon measures for the sectors, the result indicates a negative weighted average cost of US\$21.96/tCO_2 tied to a mitigation potential of 68.4 million tons of CO_2 by the year of 2030.

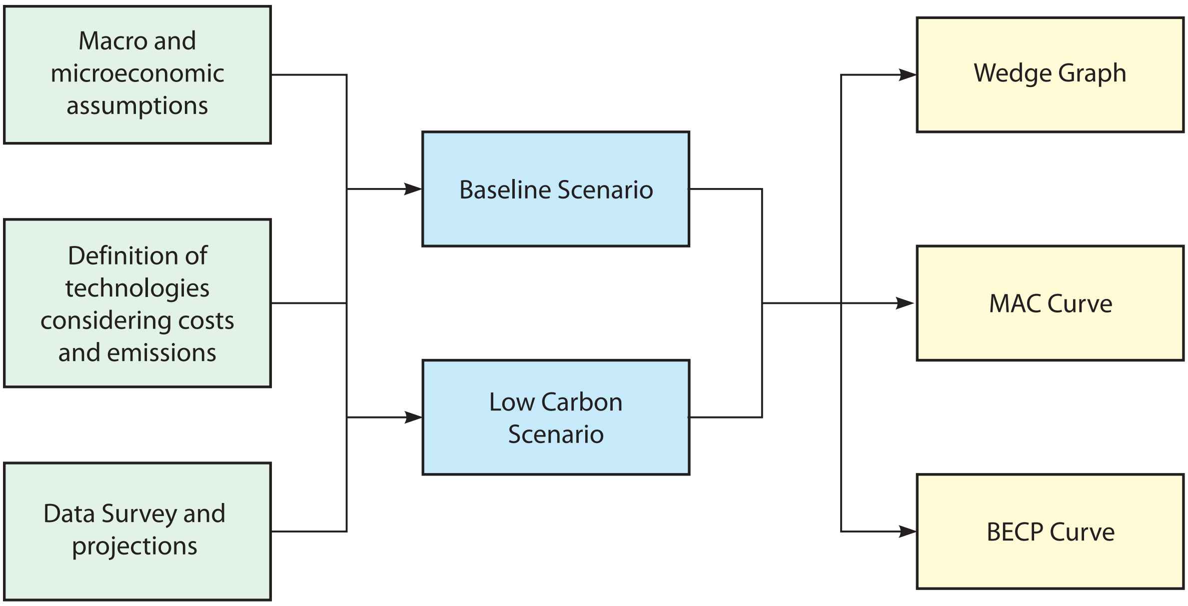
STUDY DEVELOPMENT STAGES

The construction of the scenarios followed the framework presented in **Figure 1**, which includes an initial data survey, the establishment of assumptions and the development of projections. Subsequently, the scenario (BS) and low carbon scenario (LCS) as well as MAC and BECP results were presented, together with the Wedge Graph showing the mitigation potentials.

GHG emissions were estimated using the method presented in the Guide to the Good Practice Guidance and Uncertainty Management in Natural Greenhouse Gas Inventories of the Intergovernmental Panel on Climate Change (IPCC, 2000b) . These estimates considered activity data such as production or energy consumed and the respective emission factor (EF).

The approach used to determine the MAC and BECP1 was incremental and based on the Low Carbon Study for Brazil (GOUVELLO *et al.*, 2010). The MAC and BEPC curves were constructed using the MACTool, which according to the Energy Sector Management Assistance Program (ESMAP, 2016) was developed by the World Bank for this purpose. The tool also enables assessing the total investment needed to make changes for moving towards a low

Figure 1 – Study development stages



Source: Pacca *et al.* (2017)

1. The break-even price of carbon indicates the economic incentive that economic agents such as industry would need to make the proposed mitigation measure attractive vis-à-vis the benchmark. This price is determined in the same way as the marginal abatement cost, but using the benchmark internal rate of return (IRR). Usually, the benchmark carbon price is presented graphically in the same way as the MAC curve (GOUVELLO *et al*, 2010).

carbon growth and can be used to test different possibilities by exploring sectors and price responses. As inputs, the MACTool uses key values to characterize mitigation measures and for macroeconomic variables, and users must specify at least one scenario for the macroeconomic future including variables of interest such as the price and future demand for fossil fuels and provide scenarios for the future adoption of low carbon technologies or measures for a baseline, and at least one emission reduction pathway (FAY *et al.*, 2015).

Figures showing mitigation wedges (Wedge Graphs) have been produced to assess the GHG emission reduction potential of each technology in quantitative terms. These wedges summarize results from the comparison between the BS and the LCS considering the implementation of the respective technologies. This information enabled visualizing the potential of each technology to GHG mitigation.

RESULTS

This section presents results for the period 2014 to 2030 on the evolution of industrial production in the state, evolution of energy consumption and evolution of emissions in the BS and LCS, as well as investment costs, emissions avoided by each measure in both scenarios, the marginal abatement cost (MAC curve), and the BECP of each technology.

EVOLUTION OF INDUSTRIAL PRODUCTION IN SAO PAULO STATE

Compared with previous studies, which generally link the future to a single macroeconomic scenario, in this study the scenarios of evolution of physical production in each industrial sector are different and were characterized according to the perspectives of specialists from each sector. Thus, there are situations in which future production will decrease, as is the case of the lime industry.

In the lime industry, a future reduction in the production of slaked lime for construction has been considered as a result of the migration from mortar produced in the construction site to factory produced mortar. This reduction in amount, according to the study, will also occur due to the replacement of lime with other chemicals known as air incorporators (FREITAS; VOGELAAR, René; VOGELAAR, Renato, 2017a).

In the steel industry, the operation of the single blast furnace that produced pig iron in the state was halted and it is expected that it will resume its operation in 2022, and grows at a constant proportion of 1.5 in relation to Brazil's Gross Domestic Product (GDP). As an example, in the year when the country's GDP increased by 1.5%, steel production grew by 2.25%. Increases in the installed capacity of the semi integrated route, which makes steel from scrap using electric arc furnaces (EAF) have also been considered. In 2015, the SIMEC plant in Pindamonhangaba began operations, with 350,000 tons per year. An increase in capacity of 850,000 tons per year is expected by 2030, as a result of the expansion of two plants in the semi integrated route (FREITAS; VOGELLAR, René; VOGELAAR, Renato, 2017b).

In the chemical industry, a growth rate of 0.37% p.a. was considered, but there will be no increase in installed capacity in the state. Therefore, production will grow until it stabilizes at circa 3.5 million tons in 2027. Thus, the average annual growth in the period 2014 2030 will be 1% p.a. This is also the only sector in which production in the BS differs from that in the LCS, which will experience an increase of 247,000 tons of bioethene starting from 2025 (FANTI *et al.*, 2017).

Finally, the output of the cement sector was subject to a severe reduction between 2014 and 2018 but subsequently an annual growth rate of 4% was considered starting in 2020. No increase in installed capacity via the integrated route is expected. Production through this route will stabilize at 5.2 million tons in 2030 (PUNHAGUI *et al.*, 2017).

Chart 1 shows the evolution of and comparison between the production scenarios for each industrial sector considered in the study. The production scenarios were instrumental in determining the energy consumption scenarios and the scenarios resulting from GHG emissions in the BS and subsequently in the LCS.

Evolution of energy consumption by the industrial sectors included in the project

Projected energy consumption to 2030 for each sector of the study is presented in **Table 1.**

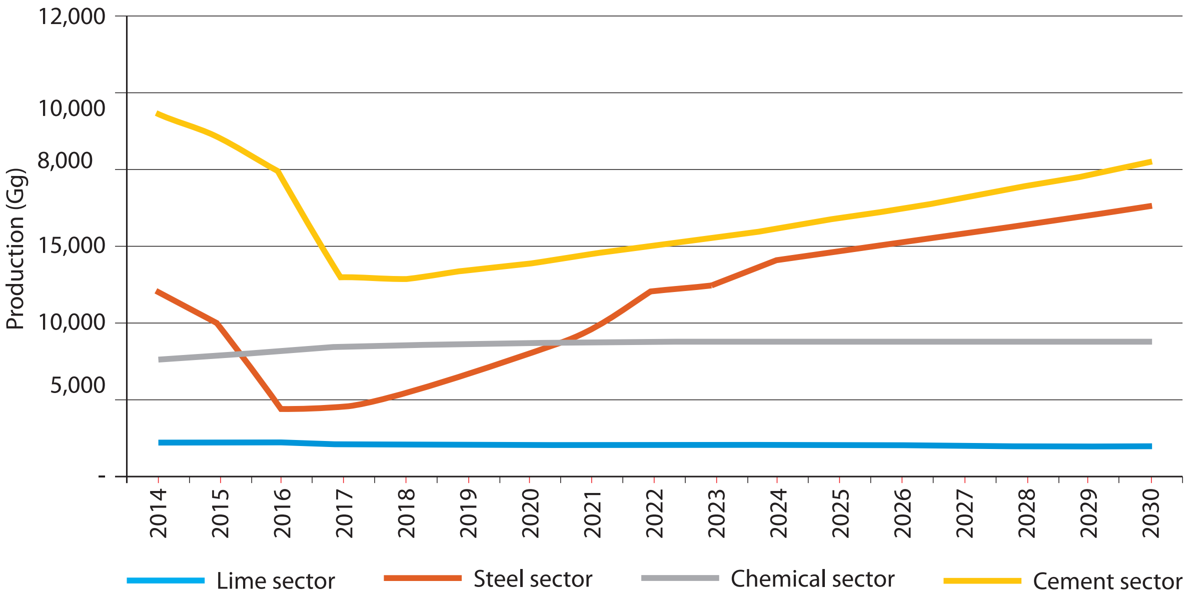
Energy consumption has a great weight in determining the GHG emission scenario,

Table 1 – Projected energy consumption for Sao Paulo's industrial sectors

Year	Lime	Steel	Chemical	Cement	Total
	(TJ)				
2014	4,405	87,780	79,796	17,633	189,614
2015	4,408	75,240	82,221	15,800	177,669
2016	4,374	29,469	85,188	13,235	132,266
2017	4,340	29,678	84,812	7,932	126,762
2018	4,307	35,990	79,044	7,913	127,254
2019	4,238	37,339	79,324	8,299	129,200
2020	4,241	38,740	81,579	8,812	133,372
2021	4,209	40,192	82,648	9,345	136,395
2022	4,177	41,700	82,742	9,900	138,520
2023	4,146	43,263	82,808	10,477	140,695
2024	4,149	44,886	82,877	11,077	142,989
2025	4,119	46,569	82,947	11,702	145,337
2026	4,088	48,315	83,021	12,351	147,775
2027	4,024	50,127	83,023	13,026	150,200
2028	3,962	52,007	83,023	13,728	152,719
2029	3,900	53,957	83,023	14,458	155,338
2030	3,841	101,751	83,023	15,218	203,832

Source: Freitas, René Vogelaar and Renato Vogelaar (2017a, 2017b), Fanti *et al.* (2017) and Punhagui *et al.* (2017) apud Pacca *et al.* (2017)

Chart 1 – Projected production of the industrial sectors addressed in the study for Sao Paulo



Source: Freitas, René Vogelaar and Renato Vogelaar (2017a, 2017b), Fanti *et al.* (2017) and Punhagui *et al.* (2017) *apud* Pacca *et al.* (2017)

mainly due to the composition of the energy matrix of each industrial sector.

In the lime industry, 100% of the thermal energy consumed is supplied by firewood from planted forests (FREITAS; VOGELAAR, René; VOGELAAR, Renato, 2017a). As a result, for the BS it was considered that energy efficiency in this industry could be used to move firewood to other sectors that still use fossil fuels such as petroleum coke.

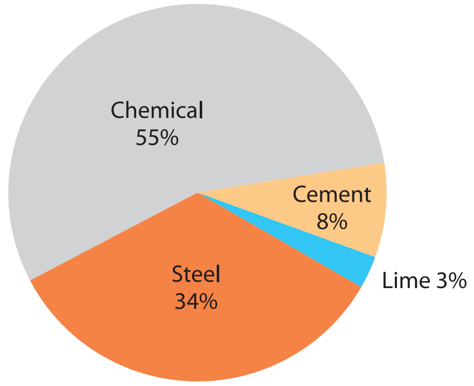
In the steel industry a distinction is observed between the integrated and semi integrated routes. In the integrated route, electricity represents only 10% of the total energy consumed, whereas in the semi integrated route it accounts for 24% of the total (FREITAS; VOGELAAR, René, VOGELAAR, Renato, 2017b). This shows that the semi integrated route is more attractive in terms of opportunities that involve electrical efficiency.

In the chemical industry, despite the diversity of energy types consumed, it is observed that 49% of the total energy corresponds to electricity and 39% to natural gas. There is a strong relation between these two types of energy, since thermal energy from natural gas can be used in the cogeneration of electricity, as seen in the sectoral study by Fanti *et al.* (2017).

In the cement industry, only 8% of the energy consumed refers to electricity. Because of that and of the low EF of electricity in relation to the EF of petroleum coke, which is the fossil fuel used in cement kilns, electricity emissions become negligible, which makes strategies based on electrical efficiency little attractive to the sector.

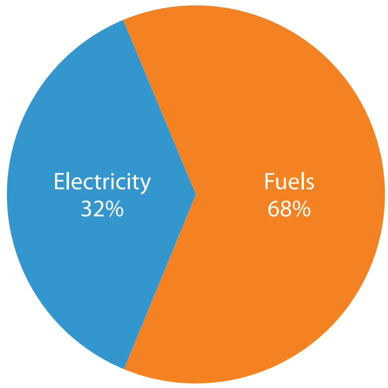
Chart 2 shows that the chemical industry accounts for 55% of the total energy consumed in the period, followed by the steel industry with 34%. **Chart 3** shows that the share of thermal energy is 68% of the total against 32% of electricity.

Chart 2 – Total energy consumption by industrial sector – 2014–2030



Source: Pacca *et al.* (2017)

Chart 3 – Share of electricity and thermal energy in total consumption – 2014–2030



Source: Pacca *et al.* (2017)

Evolution of emissions from Sao Paulo's industrial sectors in the baseline scenario

Table 2 shows the emissions from the Lime, Steel, Chemical and Cement industries in the BS in the period 2014-2030.

Table 2 shows the emissions from the Lime, Steel, Chemical and Cement industries in the BS in the period 2014 2030.

Considering the total emissions in the period, the largest share of emissions refers to the chemical industry with 55%, followed by the steel industry with 32%, the cement industry with 11% and finally the lime industry with 2%.

Comparing the 2014 BS with the year 2030, there is a 13% reduction in emissions from the lime industry, a 33% increase in the steel industry, a 20% increase in the chemical industry, a 14% reduction in emissions from the cement industry and a 19% increase considering total emissions. In absolute terms, emissions by 2030 would total of 360 million tons of CO_2.

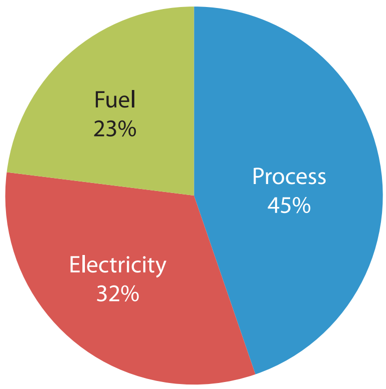
As for the origin of emissions, shows the share in total emissions for the period 2014 2030. Process emissions account for 44.7%, while the remaining 55.3% account for both electricity and thermal energy.

Table 2 – Emissions from the BS in industrial sectors – 2014–2030

Year	Lime	Steel	Chemical	Cement	Total
	($GgCO_2e$)				
2014	588	8,051	10,65	3,466	22,755
2015	589	6,572	10,784	3,077	21,021
2016	584	1,755	11,101	2,54	15,98
2017	579	1,764	11,256	1,489	15,088
2018	575	2,109	11,058	1,488	15,229
2019	566	2,311	10,569	1,567	15,013
2020	566	2,745	11,029	1,673	16,013
2021	562	2,847	11,355	1,783	16,546
2022	557	8,326	11,497	1,898	22,278
2023	553	8,637	11,647	2,017	22,854
2024	554	8,96	11,798	2,14	23,451
2025	549	9,294	12,054	2,269	24,166
2026	545	9,642	12,186	2,403	24,776
2027	536	10,002	12,414	2,542	25,495
2028	528	10,366	12,552	2,687	26,133
2029	520	10,701	12,671	2,838	26,729
2030	512	10,725	12,808	2,994	27,038

Source: Freitas, René Vogelaar and Renato Vogelaar (2017a, 2017b), Fanti *et al.* (2017) and Punhagui *et al.* (2017) apud Pacca *et al.* (2017)

Chart 4 – Share of CO_2e emissions by origin in the period 2014–2030



Source: Pacca *et al.* (2017)

Low-carbon measures surveyed in the study and the penetration scenario

Table 3 shows the list of low carbon technologies and measures surveyed and evaluated. The table also shows the first year of implementation of each technology and measure, some of which are one time actions, such as Carbon Capture and Storage (CCS) and the bioethene plant in 2025, while others are gradually implemented over the period, such as the replacement of Azbe kilns with Maerz kilns in the lime industry and of traditional lighting with LED bulbs in the chemical industry.

In the short term (2014–2019), ten of the seventeen measures would already be under implementation at some level of penetration. In the medium term (2020–2024), three more measures would be implemented, two of them in the process side of the chemical industry and one in the semi integrated route of the steel industry. In the long term (2025–2030), four more measures would be implemented, including the CCS system and the TGRBF MDEA.

Table 3 – Measures in the LCS using the MACTool

Sector	Measure	Scenario of implementation
Chemical	Natural gas cogeneration	Short term
	Replacement of traditional lighting with LED bulbs	Short term
	Implementation of more efficient electric motors	Short term
	Replacement of fuel oil with firewood	Short term
	Replacement of natural gas with firewood	Short term
	Recovery of purge gas in ammonia	Mediun term
	Catalytic conversion of nitrous oxide (N_2O) in nitric acid production	Mediun term
	Production of bioethene (ethene from ethanol) Natural gas cogeneration	Long term
Lime	Carbon Capture and Storage (CCS)	Long term
	Replacement of Azbe kiln with Maerz kiln using firewood in natura	Short term
	Replacement of Azbe kiln with Maerz kiln using torrefied firewood	Long term
Steel	Top Gas Recycling Blast Furnace – Metildietanolamine (TGRBF-MDEA)	Long term
	Continuous feed and scrap preheating furnace (CONSTEEL System)	Short term
	Direct-current (DC) furnaces	Mediun term
Cement	Replacement of fossil fuels with Refuse-Derived Fuel (RDF)	Short term
	Replacement of fossil fuels with wood pellets	Short term
	Increase in filler content in cement	Short term

Source: Pacca *et al.* (2017)

Emissions avoided in the low carbon scenario

The mitigation of GHG emissions is shown in **Table 4**. It can be concluded that the implementation of the seventeen measures analyzed will enable reducing 68.4 million tons of CO_2 or 19% of total emissions in the BS from 2014 to 2030.

From the industry standpoint, the most outstanding emission mitigation potential is that of avoided emissions from the chemical industry, which represent 46% of the total mitigation potential assessed by the present study, with 95% of this potential stemming from measures related to energy consumption. The steel and cement industries come next, with 29% and 19 % of the total avoided respectively. Lastly, we have the lime industry with 5%. About this result, the size of the industry and the consequent amount of emissions in relation to the other sectors of Sao Paulo's industry analyzed in the study should be considered.

Table 4 – Emissions avoided in the low carbon scenario by industrial sector

Year	Avoided emissions				Total Emissions LCS	Total Emissions BS
	Lime Industry	Steel Industry	Chemical Industry	Cement Industry		
($GgCO_2$)						
2014	0	-	-	46,096	22,708,588	22,754,684
2015	0	-	110,26	51,316	20,859,051	21,020,627
2016	0	-	386,554	124,731	14,673,378	15,184,663
2017	0	11,594	655,844	194,779	14,226,084	15,088,301
2018	0	11,927	940,835	298,597	13,977,966	15,229,324
2019	31,749	12,27	1,238,686	409,47	13,320,538	15,012,713
2020	31,775	41,016	1,517,380	503,922	13,919,213	16,013,305
2021	63,07	42,502	1,705,284	605,765	14,129,551	16,546,172
2022	62,596	58,695	1,893,087	712,53	19,551,266	22,278,174
2023	93,191	60,823	2,200,493	824,51	19,674,949	22,853,965
2024	93,271	63,027	2,376,588	942,011	19,976,229	23,451,127
2025	560,31	3,026,903	2,652,057	1,065,354	16,861,660	24,166,284
2026	556,095	3,140,310	2,851,282	1,194,873	17,033,235	24,775,796
2027	580,797	3,269,032	3,017,425	1,330,922	17,296,646	25,494,821
2028	571,664	3,391,281	3,208,198	1,473,867	17,487,885	26,132,895
2029	562,73	3,505,462	3,260,027	1,624,096	17,776,670	26,728,985
2030	553,989	3,505,925	3,297,473	1,783,296	17,897,354	27,038,037

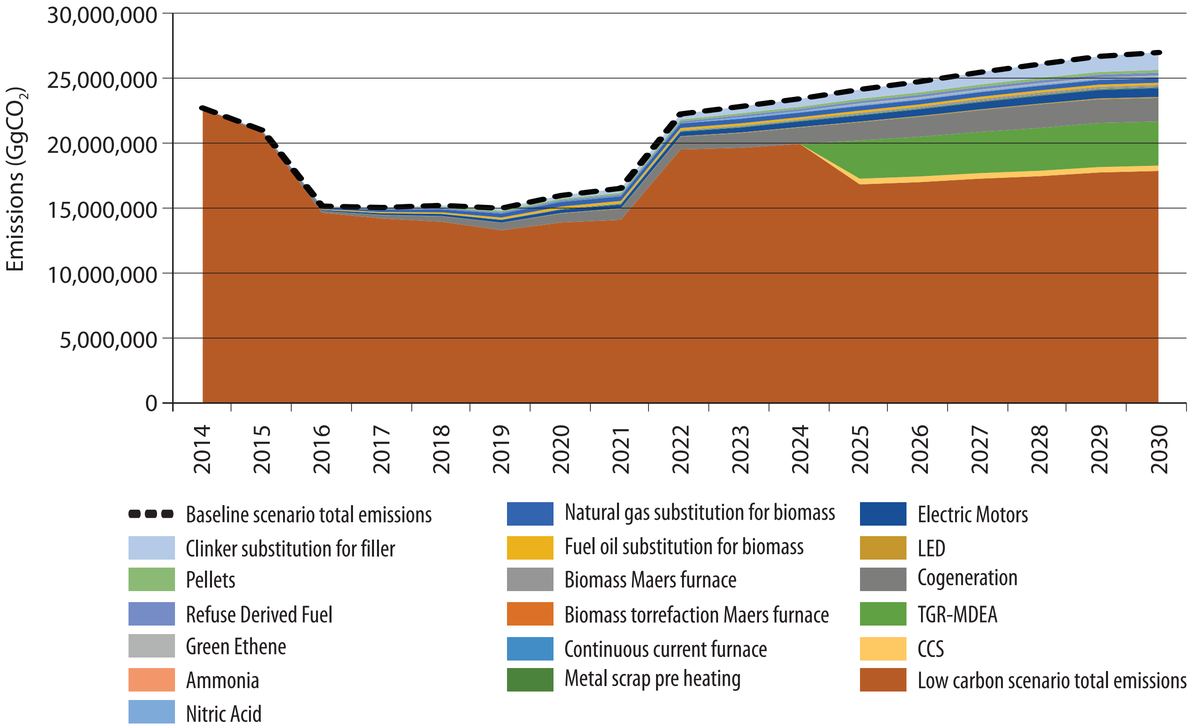
Source: Pacca *et al.* (2017)

From the standpoint of the measures, the largest share in total avoided emissions is that of the TGRBF MDEA technology in the blast furnace of the steel industry, with 28%. Particularly, the blast furnace is present in the production process through the integrated route of the steel mill and, in the State of Sao Paulo, it is present in one plant only, USIMI NAS, which was shut down at the end of 2015 (FREITAS; VOGELAAR, René; VOGELAAR, Renato, 2017b). Although USIMINAS shut down the blast furnace in 2015, for the purpose of the study it was considered that furnace will resume its operation in 2022. A parallel analysis shows that if the blast furnace remained shut down until the year 2030, considering its maximum production capacity, 104 million tons of CO_2 emissions would be avoided over a 15 year period. This represents 72% of total emissions from the steel industry in the BS or 24% considering all industrial sectors.

In second place is the cogeneration measure in the chemical industry, with a share of 21% in avoided emissions. As seen below, this measure has a low MAC value, which coupled with its reduction potential can deliver considerably monetary savings.

In third place is the measure that increases the use of filler in the cement industry, with a 19% share in avoided emissions. This measure also has a negative MAC and, therefore, generates savings when compared to the BS.

Chart 5 – Emissions avoided by low carbon measures



Source: Pacca *et al.* (2017)

Marginal abatement cost (MAC curve) and break-even carbon price of low carbon measures

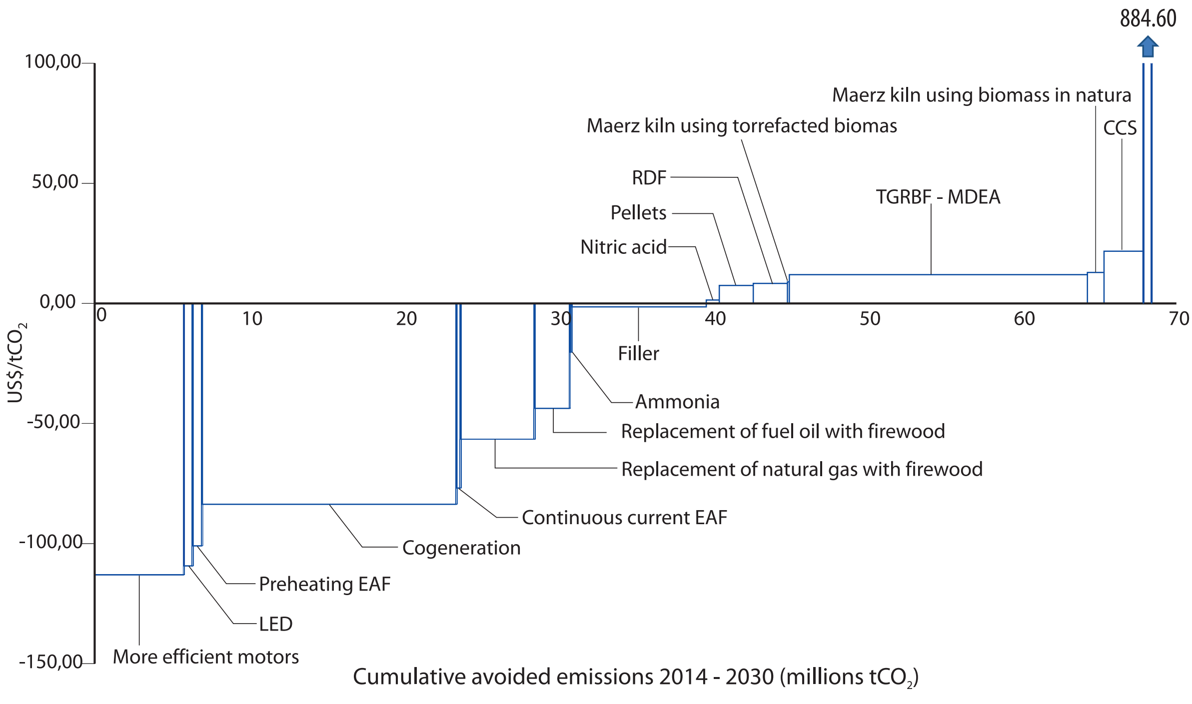
Chart 6 presents the MAC curve with the seventeen measures assessed in the study.

Table 5 shows nine measures for which the economic result is negative. These measures are known as 'no regrets'2, that is, the measures do not represent a cost to society and may even lead to gains. Among these measures, the most attractive are those related to the decrease in both cement and energy consumption. The fourth measure is cogeneration in the chemical sector, which can also be considered as an energy loss reduction measure.

If only no regret measures were adopted, USD2.56 billion would be saved by 2030, with a total reduction of 39.58 million tons of CO_2, or 58% of the total mitigation potential assessed. If the choice were to reach the total potential of 68.4 million tons of CO_2, an economic gain of USD1.7 billion would still be generated. These overall economic results will vary if considered individually for each sector.

The BECP results show that few measures change position in relation to the ascending order of cost. In the BECP, there was basically an increase in values (in module) in relation to the MAC curve, due to the IRR Benchmark rates, which for all sectors are higher than the social discount rate used to calculate the MAC. In total, eight low carbon technologies bring an internal rate of return (IRR) above that determined as an IRR Benchmark rate for the sector, which makes them attractive investments. As for the other technologies, for this to happen the ton of carbon needs to be sold at the BECP found in the study.

Chart 6 – Marginal Abatement Cost Curve for Sao Paulo's industry



Source: Freitas, René Vogelaar and Renato Vogelaar (2017a, 2017b)

Table 5 – MAC curve values for Sao Paulo's industrial sectors

Type of emission	Measure	MAC	BECP	Avoided emissions 2014–2030
		(US$/t$CO_2$)	(US$/t$CO_2$)	(MtCO_2)
Electricity	More efficient motors	– 113,02	– 168,78	5.77
Electricity	LED	– 109,26	– 168,78	0.57
Electricity	Preheating and continuous feed	– 100,97	– 217,01	0.61
Electricity	Cogeneration	– 83,64	– 188,37	16.46
Electricity	Direct current furnace	– 76,86	– 172,55	0.27
Fuel	Replacement of NG with reforestation wood	– 56,51	– 98,71	4.79
Fuel	Replacement of FO with reforestation wood	– 43,70	– 77,61	2.28
Process	Ammonia	– 20,34	7,53	0.06
Process and Fuel	Filler	– 1,51	– 3,77	8,77
Process	Nitric acid	1,51	23,36	0.84
Fuel	Pellets	7,53	17,33	2,21
Fuel	RDF	8,29	18,08	2,21
Fuel	Maerz kiln using torrefied biomass	9,04	70,08	0.13
Process	TGRBF-MDEA	12,06	71,58	19.27
Fuel	Maerz kiln using biomass in natura	12,81	70,83	1.09
Process	CCS	21,85	73,84	2.54
Process	Bioethene	884,60	2943,91	0.54

Source: Freitas, René Vogelaar and Renato Vogelaar (2017a, 2017b) and Punhagui *et al.* (2017).

CONCLUSIONS

This exploratory study allowed a quantitative evaluation of emissions and costs resulting from the seventeen options analyzed, to inform decision makers committed to tackling the climate issue. The study addressed the mitigation potential of actions related to thermal energy and electricity efficiency; of the replacement of fossil fuels with renewable energy; and finally of the introduction of aggressive measures such as CCS and TGRBF MDEA. This is an unprecedented study in the state for low carbon development in Sao Paulo's industrial sectors.

Among the seventeen measures analyzed, nine showed a negative cost, i.e., adopting them to the detriment of the projected BS would be beneficial. All 17 measures for the four sectors assessed would have the potential to mitigate 68.4 million tons of CO_2 by the year 2030. The average MAC result, weighted by the mitigation potential, indicates a negative amount of USD 21.96/tCO_2.

From the standpoint of the reduction targets set by PEMC, the results of the study show that there are several possibilities for achieving them and that both the economic context and the market can facilitate the reduction of emissions through no regret measures or even spontaneous measures. However, the presence of the State through regulations is necessary for the reduction targets to be achieved in an efficient, effective and economically viable manner.

In this context, the survey of carbon prices (MAC and BECP) can ensure that the most attractive reduction options will be adopted more easily and that organizations will equalize marginal to guarantee the necessary means for a low carbon transition. However, it is worth bearing in mind that besides considering assumptions, the MAC curve is dated for a reference year and a specific period. In this sense, the results of this exploratory study are a starting point for the discussion of mitigation possibilities of Sao Paulo's industrial sectors.

Finally, special mention should be made of the limitations and difficulties experienced during the preparation of this document, which had among its main objectives the identification of possible directions for a low-carbon future with a specific and exploratory approach to the lime, cement, chemical and steel sectors in the State of Sao Paulo. As decision makers choose certain paths, new studies should emerge to broaden the scope and deepen the technical, political, regulatory, social and environmental character of these low carbon technologies. It should be highlighted that this study has focused on the analysis of technologies to mitigate greenhouse gas emissions and, therefore, the emission of other pollutants should be analyzed according to the current legislation, which sometimes requires the regulation of specific procedures.

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