Low Carbon Study for São Paulo's Industrial Sector 2014•2030

Summary Report

1 updated edition

Government of the State of São Paulo

Secretariat of Infrastructure and Environment

CETESB – Environmental Agency of the State of São Paulo

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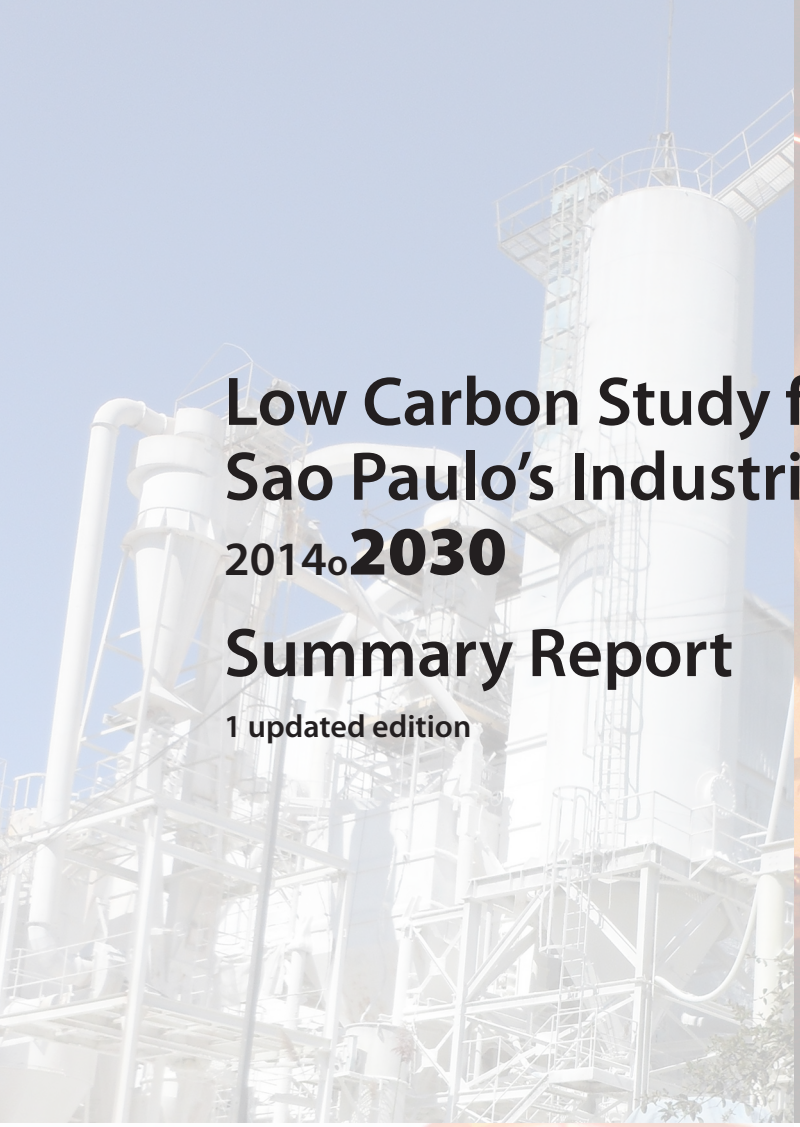
São Paulo, 2019



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Estudo de Baixo Carbono para a Indústria de Cal no Estado de São Paulo de 2014 a 2030
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Estudo de Baixo Carbono para a Indústria Siderúrgica no Estado de São Paulo de 2014 a 2030
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The World Bank, through its technical assistance fund, ESMAP, supported the development of this study with the MACTool and the information necessary for using it. For the latest version of the tool visit http://esmap.org/mactool (access on 12/01/2017).

Introduction by the Secretary

Celebrating 10 years of the State Climate Change Policy (Política Estadual de Mudanças Climáticas - PEMC) promulgated through Law No. 13,798, we published the Summary Report "Low Carbon Study for São Paulo's Industrial Sector 2014-2030", 1st updated edition, in English.

Having been prepared under the coordination of the Climate Change Program (PROCLIMA) of the São Paulo State Environmental Company (CETESB) with the support of the Inter-American Development Bank (IDB) and expert researchers, this study considered low-carbon technology scenarios of four major industry sectors, steel, chemical, lime and cement (including civil construction), and analyzes the costs and opportunities in the implementation of new low carbon technologies.

This pioneering study, with exploratory objectives and voluntary action proposals for the sector, is the summary of a few years partnership with the IDB, which has brought together professionals from various institutions and companies and was subjected to a broad process of public consultation, with the participation of professionals from the studied sectors. This publication contributes to the implementation of the objectives of the State Climate Change Policy (PEMC), articulating the knowledge of different institutions and agencies of the state government, for the development of studies and voluntary projects of mitigation of greenhouse gas emissions.

Marcos Penido
Secretary of Infrastructure and Environment

Introduction by the President

The "Project for the Development Greenhouse Gas Mitigation Study for the State of São Paulo", developed by the São Paulo State Environmental Agency (CETESB) and expert researchers, is an important tool for promoting a more sustainable and low-cost carbon economy. Sponsored by the Inter-American Development Bank Cooperation (IDB), the assessment has outlined a baseline of greenhouse gas (GHG) emissions for 2014 and projected exploratory scenarios up to 2030, taking into account the most emission intensive sectors for the state of São Paulo: steel, chemical, lime and cement sectors. Numerous possibilities for technologies for voluntary GHG reduction and their possible implementation costs were evaluated. Based on these scenarios, Marginal Abatement Costs (MAC) were estimated and used to generate the Marginal Cost Abatement Curve (MAC Curve), this tool was developed by the World Bank, and used to generate the results.

The breakeven internal rate or return for projects in each sector was also established in the study to generate the Break-Even Carbon Price (BECP) curve. Emission reductions provided by each technology option were consolidated in a Wedge Graph. This document presents an exploratory, innovative result of extreme technical and institutional importance of the technical cooperation and allows us to contribute to the dissemination of relevant knowledge, so that other actors from Brazil and Latin America and the Caribbean can also rely on an adequate basis for their efforts to mitigate the effects of climate change.

The partnership between CETESB and the IDB is part of the environmental agency's effort to generate information and foster the development of the low carbon industry, seeking strategic solutions in response to the State Climate Change Policy (PEMC), contributing to the effort of reducing carbon intensity associated with state development, without thereby compromising industry and employment growth targets.

Patrícia Iglecias
Director President

Introduction by the IDB Representative in Brazil

During the annual meeting of its Board of Governors in 2016, the Inter-American Development Bank (IDB) approved the target of doubling the financing for climate-related projects, which should account for 30 percent of the IDB Group's loan approvals by 2020. The target, although subject to demand from borrowing countries and clients and access to external sources of financing, is a fundamental guideline for our work in the region. Thus, the IDB strengthens its strategic action role in mitigating environmental impacts and climate change effects, focusing on projects that can help Latin American and Caribbean countries meet their commitments made at the Conference of the Parties (COP 21) held in Paris in 2015.

The partnership between the IDB and the State of Sao Paulo (CETESB) in the "Project for the Development of Greenhouse Gas Mitigation (GHG) Studies for the State of Sao Paulo" is in line with the Bank's efforts to guide and help enable the development of the low carbon industry. The information collected using the MACTool - Marginal Cost Abatement Curve - showed technological alternatives and clear possibilities for reductions in the future, based on the efficient management of inputs - mainly in the use of energy – by presenting opportunities to reduce GHG emissions, decrease costs and increase productivity.

By supporting the State of Sao Paulo through CETESB, the IDB seeks to bring strategic solutions in response to the State Climate Change Policy (PEMC), and contributes to the state's efforts to promote the reduction of carbon intensity associated with development, without compromising the growth targets set for the industrial sectors.

This partnership represents a pioneer and extremely important technical and institutional experience. This publication shares the results of this technical cooperation process and allows us to contribute to the dissemination of relevant and innovative knowledge, so that other actors in Brazil as well as in Latin America and the Caribbean can also rely on a solid foundation in their efforts to mitigate the effects of climate change.

Hugo Florez Timoran
IDB Representative in Brazil

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We wish to express our sincere thanks to the Inter-American Development Bank (IDB) for the partnership and follow-up of this study. We thank the IDB staff for making all the necessary arrangements for the study to be completed, as well as for the reviews and suggestions that led to its improvement, notably Luciano Schweizer, Maria Netto and the IDB contractors who supported this study — Simone Bauch, Mônica Conceição, Rogério Lessa da Paixão, Andreza Leódido, and Sarah Rodrigues da Cunha Irff.

Our recognition and gratitude to the World Bank through Christophe de Gouvello and its technical assistance fund, ESMAP, for supporting the development of this study with the MACTool and the information necessary for using it.

We wish to highlight and acknowledge the contributions of our co-workers: Carlos Lacava, Maria Cristina Poli, Margot Terada, Milton Norio Sogabe, Volf Steinbaun (*in memoriam*), Maria Heloisa Assumpção, Eduardo Serpa, Núbia Rejane dos Santos Lentz, Maria Cristina de Souza Leite, Fátima Carrara.

To all those involved in this project, our heartfelt appreciation.

1 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, 2011).

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, 2011). The industry is also a major energy consumer, accounting for 57.2% of the state's emissions in 2005, of which 29.4% correspond to energy consumption by the industrial sector (CETESB, 2011). 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 the performance of alternative analyzes. Therefore, it is not just about prospecting, but about building a possible future by helping to develop 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. 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$29.15/tCO$_2$ tied to a mitigation potential of 78.4 million tons of CO$_2$ by the year of 2030.

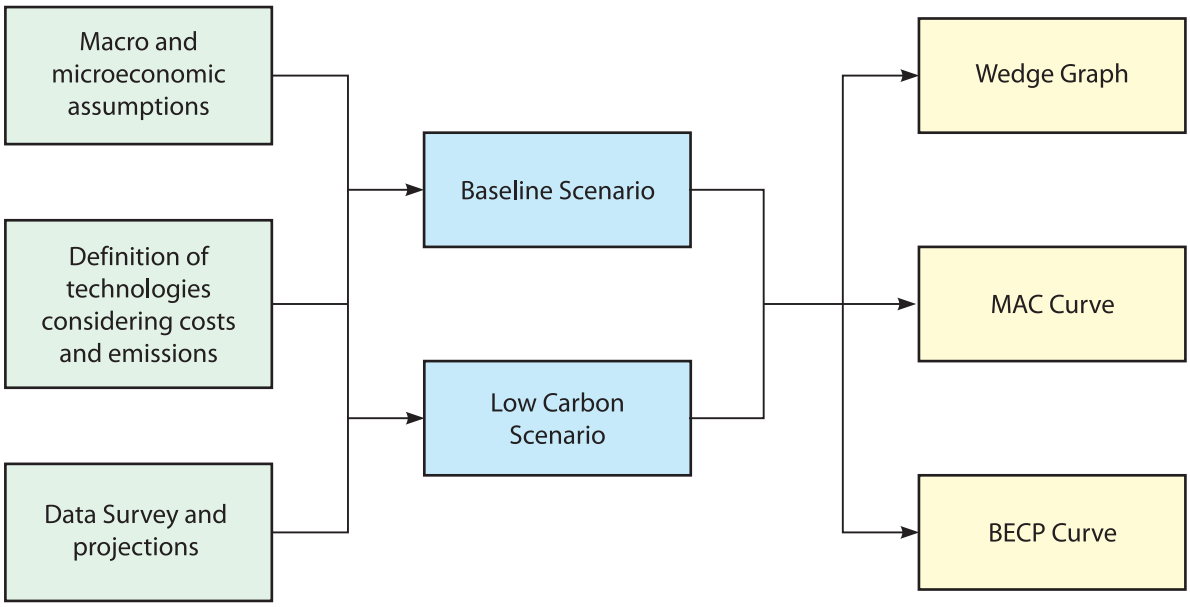
STUDY DEVELOPMENT STAGES

The construction of the scenarios followed the methodological roadmap 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 Intergovernmental Panel on Climate Change (IPCC, 2000b), the Good Practice Guidance and Uncertainty Management in Natural Greenhouse Gas Inventions. 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 BECP[1] 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-carbon growth and can be used to test different possibilities by exploring sectors and price responses. As inputs, the MACTool uses key

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, 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).

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 of and future demands 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 exploratory result from the comparison between the BS and the LCS with the implementation of the respective technologies. This information enabled visualizing the contribution of each technology to GHG mitigation.

RESULTS

This section presents the 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 conclusion is that steel production 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 3.7% p.a. was considered, but there will be no increase in installed capacity in the state. Therefore, production will grow until it stabilizes at 3.5 million tons in 2025. 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, a growth rate of 5% p.a. was considered for the cement industry starting in 2016. No increase in installed capacity via the integrated route is expected to occur. Production through this route will stabilize at 7.8 million tons in 2019, and from that year onward production will

increase through the milling route (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, mainly due to the composition of the energy matrix of each industrial sector.

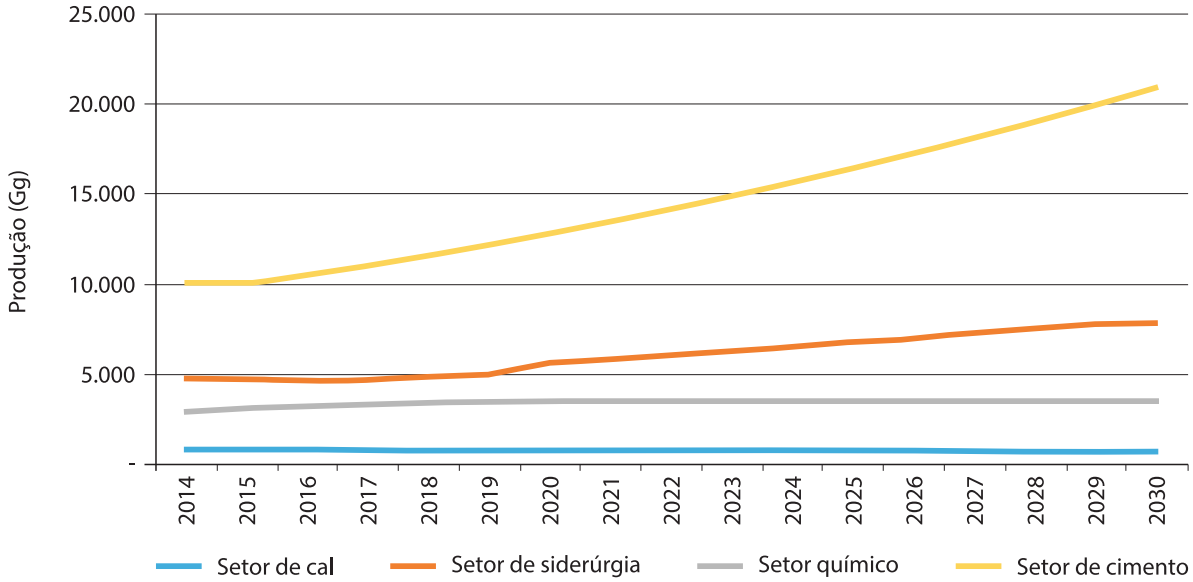
In the lime industry, 100% of the thermal energy consumed is supplied by firewood from reforestation areas (FREITAS; VOGELAAR, René; VOGELAAR, Renato, 2017a). As a result,

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

Year	Lime	Steel	Chemical	Cement	Total
	(TJ)				
2014	4,405	24,529	71,332	19,014	119,280
2015	4,408	24,707	73,923	18,684	121,723
2016	4,374	24,191	76,609	19,680	124,854
2017	4,340	24,736	79,324	20,952	129,353
2018	4,307	25,478	81,579	22,290	133,653
2019	4,238	26,242	82,648	23,698	136,826
2020	4,241	30,743	82,742	24,077	141,803
2021	4,209	31,896	82,808	24,582	143,496
2022	4,177	33,092	82,877	25,091	145,237
2023	4,146	34,333	82,947	25,601	147,028
2024	4,149	35,621	83,021	26,112	148,903
2025	4,119	36,957	83,023	26,625	150,723
2026	4,088	38,342	83,023	27,147	152,600
2027	4,024	39,780	83,023	27,673	154,500
2028	3,962	41,176	83,023	28,205	156,365
2029	3,900	42,426	83,023	28,745	158,093
2030	3,841	42,681	83,023	29,299	158,843

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)

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.

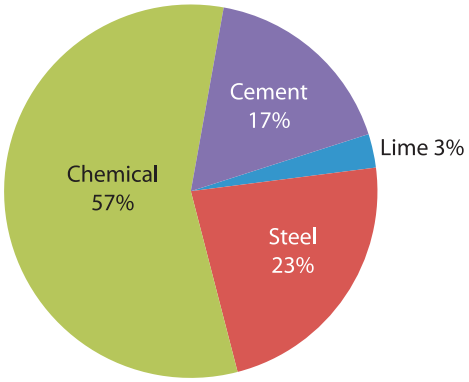
In the steel industry a distinction is observed between the integrated and semi-integrated routes. In the integrated route, electricity represents only 10% of the total energy consumed, whereas in the semi-integrated route it accounts for 24% of the total (FREITAS; VOGELAAR, René, VOGELAAR, Renato, 2017b). 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 57% of the total energy consumed in the period, followed by the steel industry with 23%. **Chart 3** shows that the share of thermal energy is 63% of the total against 37% of electricity.

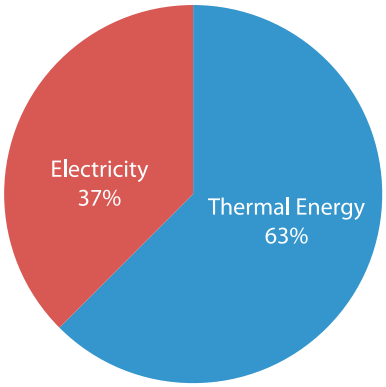
Chart 2 – Total energy consumption by industrial sector – 2014–2030



Total consumption 2014-2030: 2,423,281 TJ

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.

Considering the total emissions in the period, the largest share of emissions refers to the chemical industry with 47%, followed by the steel industry with 32%, the cement industry with 18% 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 51% increase in the steel industry, a 34% increase in the chemical industry, a 40% increase in emissions from the cement industry and a 42% increase considering total emissions. In absolute terms, emissions by 2030 would total of 442.5 million tons of CO_2.

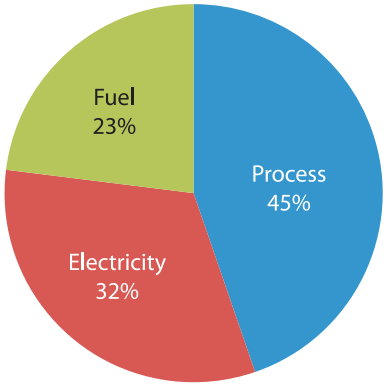
As for the origin of emissions, **Chart 4** shows the share in total emissions for the period 2014-2030. Process emissions account for 44.7%, while the remaining 55.3% account for both electricity and thermal energy.

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

Year	Lime	Steel	Chemical	Cement	Total
	($GgCO_2e$)				
2014	588	7,078	9,976	3,758	21,400
2015	589	6,830	10,333	3,676	21,428
2016	584	6,581	10,841	3,874	21,880
2017	579	6,728	11,345	4,137	22,790
2018	575	6,929	11,825	4,413	23,742
2019	566	7,136	12,152	4,702	24,556
2020	566	7,737	12,289	4,746	25,338
2021	562	8,026	12,439	4,817	25,844
2022	557	8,326	12,590	4,886	26,359
2023	553	8,637	12,740	4,953	26,883
2024	554	8,960	12,873	5,018	27,404
2025	549	9,294	13,011	5,080	27,935
2026	545	9,642	13,148	5,141	28,476
2027	536	10,002	13,267	5,200	29,005
2028	528	10,366	13,404	5,257	29,555
2029	520	10,701	13,395	5,313	29,928
2030	512	10,725	13,385	5,367	29,989

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	First year of implementation
Chemical	Natural gas cogeneration	2016
	Replacement of traditional lighting with LED bulbs	2017
	Implementation of more efficient electric motors	2015
	Replacement of fuel oil with firewood	2015
	Replacement of natural gas with firewood	2015
	Recovery of purge gas in ammonia	2020
	Catalytic conversion of nitrous oxide (N_2O) in nitric acid production	2023
	Production of bioethene (ethene from ethanol)	2025
Lime	Carbon Capture and Storage (CCS)	2025
	Replacement of Azbe kiln with Maerz kiln using firewood in natura	2018
	Replacement of Azbe kiln with Maerz kiln using torrefied firewood	2027
Steel	Top Gas Recycling Blast Furnace – Metildietanolamine (TGRBF-MDEA)	2025
	Continuous feed and scrap preheating furnace (CONSTEEL System)	2017
	Direct-current (DC) furnaces	2022
Cement	Replacement of fossil fuels with Refuse-Derived Fuel (RDF)	2016
	Replacement of fossil fuels with wood pellets	2016
	Increase in filler content in cement	2014

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 78.4 million tons of CO_2 or 18% 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 39.9% of the total mitigation potential assessed by the present study, with 95% of this potential stemming from measures related to energy consumption. The cement and steel industries come next, with 29.6% and 25.7 % of the total avoided respectively. Lastly, we have the lime industry with 4.8%. 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	Emissions avoided				Total emissions LCS	Total emissions BS
	Lime industry	Steel industry	Chemical industry	Cement industry		
	($GgCO_2$)					
2014	0	0	0	43	21,357	21,400
2015	0	0	110	48	21,270	21,428
2016	0	0	387	128	21,365	21,880
2017	0	12	656	416	21,707	22,790
2018	0	12	941	674	22,115	23,742
2019	32	12	1,239	942	22,332	24,556
2020	32	41	1,517	1,107	22,641	25,338
2021	63	43	1,705	1,279	22,754	25,844
2022	63	59	1,893	1,447	22,898	26,359
2023	93	61	2,200	1,610	22,919	26,883
2024	93	63	2,377	1,769	23,102	27,404
2025	560	3,027	2,652	1,923	19,772	27,935
2026	556	3,140	2,851	2,074	19,854	28,476
2027	581	3,269	3,017	2,221	19,917	29,005
2028	572	3,391	3,208	2,365	20,019	29,555
2029	563	3,505	3,260	2,506	20,094	29,928
2030	554	3,506	3,297	2,646	19,985	29,989

Source: Pacca et al. (2017)

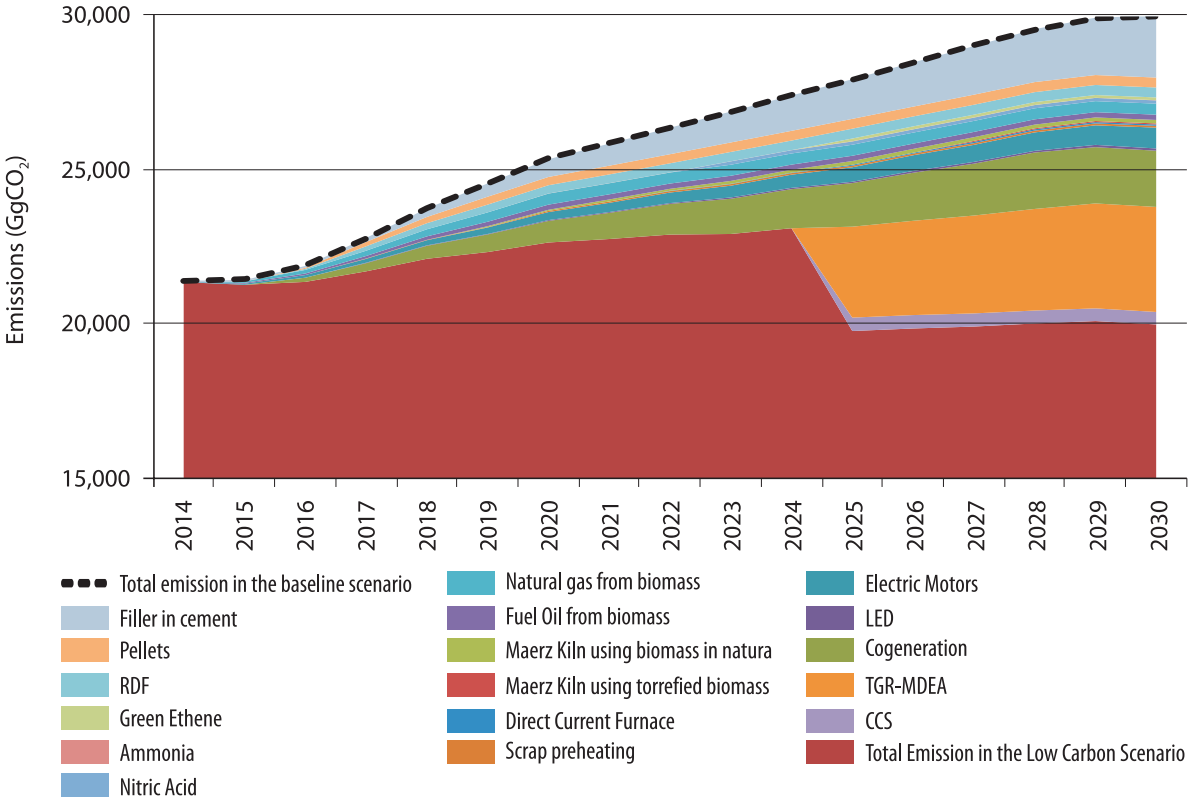
Chart 5 shows the Wedge Graph with emission reductions over the period through low carbon measures.

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 25%. 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 furnace was considered as having been operational throughout the period. 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

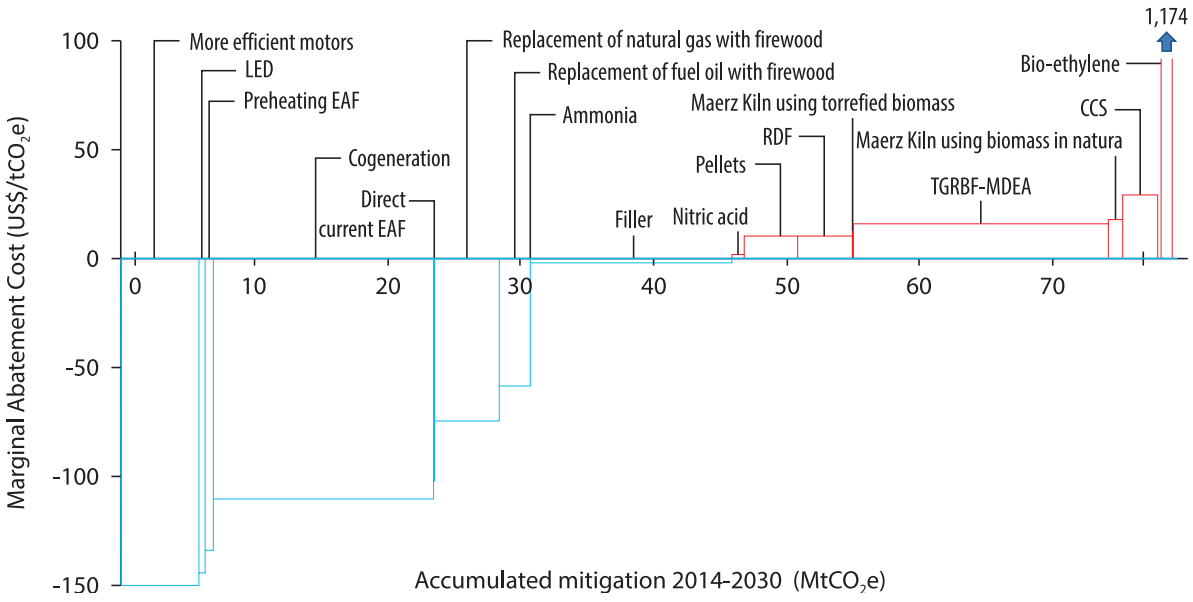
Chart 6 presents the MAC curve with the seventeen measures assessed in the study.

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, USD3.4 billion would be saved by 2030, with a total reduction of 45.95 million tons of CO_2, or 58.6% of the total mitigation potential assessed. If the choice were to reach the total potential of 78.4 million tons of CO_2, an economic gain of USD2.3 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$/tCO$_2$)	(US$/tCO$_2$)	(MtCO$_2$)
Electricity	More efficient motors	– 150	– 224	5.77
Electricity	LED	– 145	– 224	0.57
Electricity	Preheating and continuous feed	– 134	– 288	0.61
Electricity	Cogeneration	– 111	– 250	16.46
Electricity	Direct current furnace	– 102	– 229	0.27
Fuel	Replacement of NG with reforestation wood	– 75	– 131	4.79
Fuel	Replacement of FO with reforestation wood	– 58	– 103	2.28
Process	Ammonia	– 27	10	0.06
Process and Fuel	Filler	– 2	– 5	15.14
Process	Nitric acid	2	31	0.84
Fuel	Pellets	10	23	4.03
Fuel	RDF	11	24	4.03
Fuel	Maerz kiln using torrefied biomass	12	93	0.13
Process	TGRBF-MDEA	16	95	19.27
Fuel	Maerz kiln using biomass in natura	17	94	1.09
Process	CCS	29	98	2.54
Process	Bioethene	1,174	3,907	0.54

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

CONCLUSIONS

These exploratory study allowed a quantitative evaluation of emissions and costs resulting from the seventeen options analyzed, so as 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 capture 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 78.4 million tons of CO_2 by the year 2030. The average MAC result, weighted by the mitigation potential, indicates a negative amount of USD 29.15/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 pointed out that this study 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.

List of Charts

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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 Company 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

Contents

1 Introduction

This report is the consolidation of the sectoral studies carried out under the BR-T1262 Project, namely: lime, steel, chemical and cement industrial sectors. The study considered greenhouse gas (GHG) emissions from industrial processes and energy consumption. Emissions from the consumption of materials were also evaluated through the inclusion of the cement consumed by the construction industry in the state. The analysis is presented in Appendix A of this report.

The purpose of the report is to present a summary of the analysis performed and its results, including information on the main assumptions used; method of analysis; projections of variables of interest over the analyzed period; data collection on the industrial sectors modeled; and result analysis.

In the study, baseline scenarios (BS) and low carbon scenarios (LCS) were established between 2014 and 2030, considering GHG emissions from both industrial processes and energy consumption and respective mitigation alternatives. Based on these scenarios, Marginal Abatement Costs (MAC) were estimated and used to generate the Marginal Cost Abatement Curve (MAC Curve). An attractiveness rate for the sector was also established in the study to generate the Break-Even Carbon Price (BECP) curve. The reductions in emissions provided by each technology option were consolidated in a Wedge Graph.

GHG emission estimates were based on the methodological guidelines of the International Panel on Climate Change (IPCC) on Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories (IPCC, 2000a) and on the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006). These estimates were based on activity data such as physical production or energy consumed and respective emission factors.

The MAC and BECP were determined using an incremental approach and based on the *Estudo de Baixo Carbono para o Brasil* [*Low Carbon Study for Brazil* (GOUVELLO et al., 2010)]. The Marginal Abatement Cost Tool (MACTool) developed by the World Bank was used to generate the MAC and BECP curves.

To quantify the contribution of each technology to the reduction of GHG emissions, Wedge Graphs were developed showing the mitigation related to the deployment of each technology. This information enabled visualizing the contribution of each technology to GHG mitigation during the period under evaluation.

To ensure consistency and allow comparisons between final results, all the analyzes generally sought to use a common database. The base year for the analysis is 2013. Section 2 of this report presents the method used in the analyzes and common assumptions used for all industrial sectors, such as reference energy costs and carbon dioxide (CO_2) emission factors.

Section 3 provides an overview of the studies carried out by each sector, presenting the physical production, energy consumption, costs and CO_2 emission costs for both the BS and the LCS. The scenarios presented include the technologies indicated by the consultants to estimate the potential for reducing CO_2 emissions and the cost-benefit analysis of the mitigations possibilities studied. The structure of each subsection, for each specific sector, follows the same pattern to facilitate the identification of mitigation and BS and LCS possibilities, as well as their main constraints.

Next, Section 4 presents the overall results, in an integrated analysis, of the industrial sectors included in the study. It shows the curve with the

marginal cost of reducing CO_2 emissions, including the cost of the avoided ton of CO_2 and the mitigation potential by 2030 for each mitigation measure assessed. The section also discusses the results, establishes comparisons with the scenario used for Brazil (GOUVELLO et al., 2010) and presents the uncertainties of the analysis. Finally, Section 5 presents the final considerations arising from the assessments.

The report presents the assessment of 17 measures that can contribute to mitigating greenhouse gas (GHG) emissions from Sao Paulo's industrial sectors[1].

Box 1 – Scenario categorization

Descriptive	**Forecasts** use formal quantitative extrapolation and modelling to predict likely futures from current trends.
	Exploratory scenarios explore possible futures. They emphasize drivers, and do not specify a predetermined desirable end state towards which must storylines progress.
	Technical scenarios explore possible future technological systems based on hydrogen. They emphasize the technical feasibility and implications of different options, rather than explore how different futures might unfold.
Normative	**Visions** are elaborations of a desirable and (more or less) plausible future.
	Backcasts and pathways start with a predetermined 'end' point — a desirable and plausible future. They then investigate possible pathways to that point.
	Roadmaps describe a sequence of measures designed to bring about a desirable future.

Source: Adapted from McDowall and Eames (2006) apud Dixon (2011)

1.1 SCENARIOS

Future greenhouse gas (GHG) emissions are the product of very complex dynamic systems, determined by driving forces such as demographic development, socio-economic development, and technological change. Their future evolution is highly uncertain. Exploratory scenarios are alternative images of how the future might unfold and are an appropriate tool with which to analyze how driving forces may influence future emission outcomes and to assess the associated uncertainties. The possibility that any single emissions path will occur as described in scenarios is highly uncertain (IPCC, 2000).

Concerns about planning, schedules and stability often lead managers to face complex situations, in which changes require organizations to adapt to their environments (MENDONÇA, 2011). In the context of major changes and strategic planning supported by trend prospecting, the scenarios become useful tools in the planning process, with a view to informing actions that have an impact on public policies and government strategies (UFRJ; RIO DE JANEIRO, 2011).

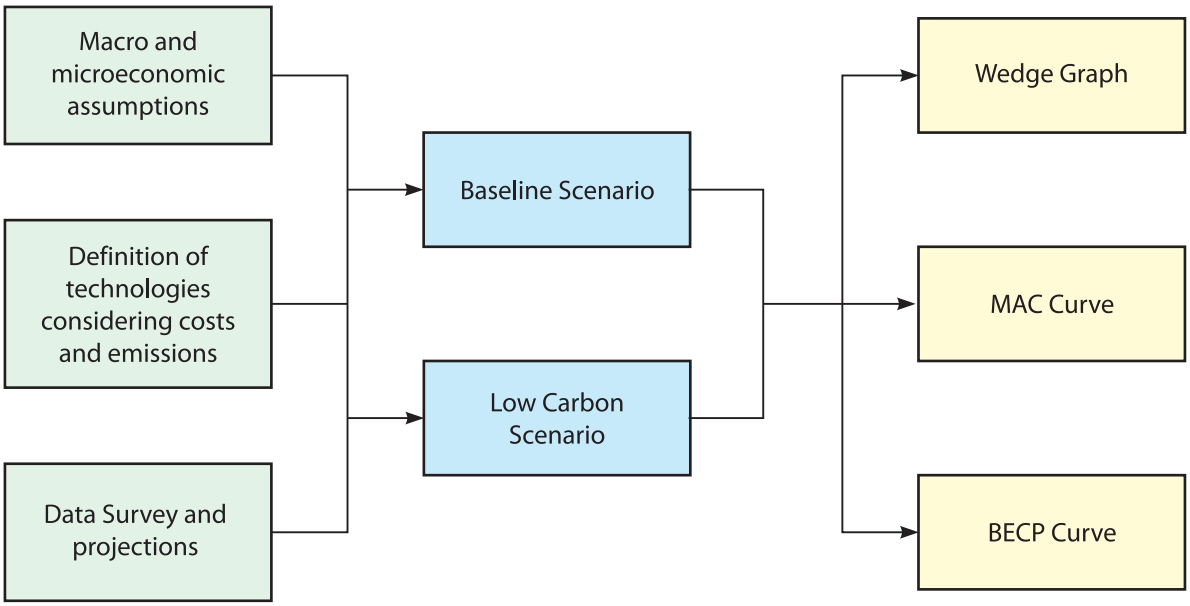
According to McDowall and Eames (2006) apud Dixon (2011), as shown in **Box 1** the scenarios are classified into descriptive or normative and subdivided into six main categories.

The scenarios constructed in this study are descriptive, since they forecast the future based on the knowledge that sectoral study experts have of the analyzed sectors. The scenarios for all industrial sectors had the features of a forecast scenario, since the projections for production, energy consumption and GHG emissions were based on current data. The steel industry study also includes an exploratory scenario, as it presented possible directions depending on whether USIMINAS will reopen or not and its impacts.

In general, the scenarios were constructed based on the methodological roadmap presented in **Figure 1**, which shows an initial data survey and projections that followed the construction of the BS and the LCS and the presentation of mitigation results, namely MAC and BECP. From the standpoint of the categorization shown in Box 1, LCSs are generally technical scenarios, since they incorporate the technologies

1. Twenty mitigation measures for the construction cement industry are presented in Appendix A.

Figure 1 – Study development stages



Source: Prepared by the authors (2019)

that reduce GHG emissions, selected by the experts from each sector. The study comprised the lime, steel, chemical and cement industries.

As for the study stages, the first ones to be completed were those related to the establishment of basic information for development, such as collection and projection of necessary data like those on production and consumption. The technologies that could be potentially used in each sector, considering emission potential, mitigation potential, energy consumption and associated costs or associated revenues were defined in the initial stage. In some cases, it was also necessary to make projections of the Gross Domestic Product (GDP).

The study scenarios were constructed based on historical data, socio-economic development assumptions such as projected GDP and consumption, information contained in sector publications, and inputs from experts. As each scenario was developed independently, the global scenario presented in this study for Sao Paulo's industrial sectors was based on a bottom-up approach.

Initially, it was necessary to recognize the way in which each industrial sector addressed has evolved in the State of Sao Paulo, considering aspects such as energy consumption and technologies already in use. Based on the current context, projections were made for the current and future conditions of energy consumption and production. These scenarios may include LCS measures already foreseen in the industry's planning horizon.

The mitigation contribution to the set of technological options by industry was recorded in Wedge Graphs. The evolution of technology deployment was based on the penetration scenarios developed by the authors.

As for the economic evaluation of both the BS and the LCS, the study provides the associated costs of implementation and operation of these technologies, the Marginal Abatement Cost (MAC) and the Break-Even Carbon Price (BECP).

2 Concepts and assumptions

This section presents the basic concepts that are part of the study methodology, the construction of the MAC Curve through the MAC-Tool, and the so-called figures of merit, which were the target of the study. Assumptions such as rates, energy prices and GHG emission factors were determined by the Project coordination unit in a way as to be common to all the analyzes, thus generating cohesion among the sectors concerned. The sources of information and calculation methods used by the coordination unit are described in the next items.

2.1 STRATEGIES FOR REDUCING GREENHOUSE GAS EMISSIONS

Brazil established the National Policy on Climate Change (PNMC) by Law 12,187 of 2009 (BRAZIL, 2009), which defines the voluntary national commitment to adopt mitigation actions, with a view to reducing their greenhouse gas emissions (GHG) between 36.1% and 38.9% in relation to projected emissions by 2020. According to Decree 7.390 of 2010 (BRAZIL, 2010), which regulates the PNMC, GHG emissions projected for 2020 were estimated at 3.2 Giga tons of carbon dioxide equivalent ($GtCO_2e$). Thus, the reduction corresponding to the percentages established is between 1.2 $GtCO_2e$ and 1.3 $GtCO_2e$, respectively, for the target year in question. The Paris Agreement was signed in 2015, during the 21st Conference of the Parties (COP 21) of the UNFCCC. The Agreement, which is already in force, establishes that each country should publish on the UNFCCC website its contribution to the reduction of GHG emissions, i.e., to submit of a Nationally Determined Contribution (NDC). In its NDC, the Brazilian government pledged to reduce its emissions by 37% by 2025, based on 2005 levels, and an additional target of 43% by 2030 (BRAZIL, 2015). These figures represent an annual reduction of 0.777 $GtCO_2e$ and 0.903 $GtCO_2e$ respectively.

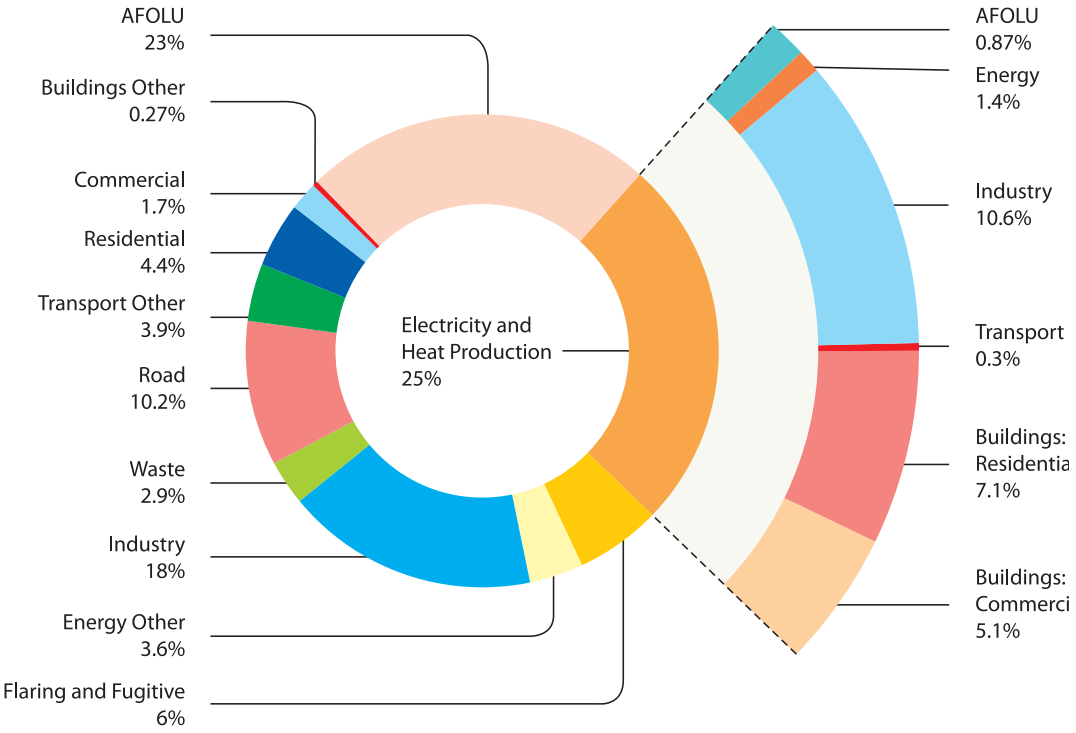
These initiatives have economic and social implications not only at the federal level, but also at the subnational (state and municipal) levels. Through Law 13,798 of November 9, 2009 (SAO PAULO, 2009), the Government of the State of Sao Paulo created the State Policy on Climate Change (PEMC) establishing the state's commitment to a 20% reduction of its emissions by 2020, based on 2005 levels (CETESB, 2011). In 2005, emissions from the State of Sao Paulo totaled approximately 140 $MtCO_2e$ (CETESB, 2011). Some strategies such as carbon taxes and cap-and-trade[2] can be adopted by governments to achieve the reductions determined by climate policies.

The contribution report of Working Group III to The Fifth Assessment Report of the Intergovernmental Panel on Climate Change – Climate Change 2014: Mitigation of Climate Change provided some information on the historical, current and future issues of global emissions considering the main GHGs related to anthropogenic activities, such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) among others. **Figure 2** shows the total global emission percentages by industry in 2010, corresponding to about 49.5 $GtCO_2e$/year. In addition to direct emissions, indirect emissions from electricity and heat production are also shown. It is noted that industry and buildings stand out as consumers of these energy vectors that account for 25% of global GHG emissions.

However, as shown in **Figure 2**, the industry is also responsible for energy consumption of (electricity and heat production) and, depending

2. Cap-and-trade refers to an environmental policy for a political unit that provides for the establishment of a common emission cap and a reduction target. The target can be met through the trade of emission reduction credits between emitters and credit holders.

Figure 2 – Global emissions, 2010



Source: Victor et al. (2014)

on the source, this consumption may result in indirect GHG emissions.

According to the GHG Inventory of the State of Sao Paulo (CETESB, 2011), in 2005 emissions in the state totaled 139,811Gg of CO_2 equivalent (excluding gases covered by the Montreal Protocol). Industry accounted for 14.4% of these emissions.

As for industrial emissions, as shown in **Chart 1** the chemical sector accounted for 38.8%, considering the production of adipic acid, phosphoric acid, nitric acid, ammonia, dichloroethane and vinyl chloride, ethene, carbon black and ethylene oxide (CETESB, 2013).

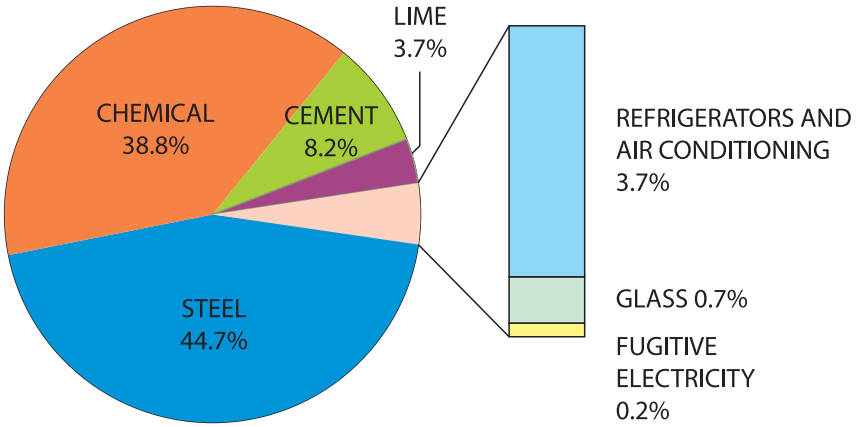
This study considers mitigation strategies that can reduce emissions from the production process and emissions from energy conversion. In addition, the study also considers the reduction of emissions from the standpoint of consumption, specific to the cement sector. This strategy is discussed in Appendix A.

2.2 FIGURES OF MERIT OF THE MACTOOL

The tool used to design the project methodology (MACTool) enables visualizing several developments from its model outputs. Four main MACTool results were addressed in this study: MAC Curve, BECP, investment intensity and CO_2 emission reduction wedges.

The emission quantification method applied in the MACTool considers emissions of the main GHGs and transforms these emissions into CO_2 equivalent emissions (CO_2e) through the Global Warming Potential (GWP). In relation to GHG types, CO_2 was the focus of this study. Only one technology related to nitric acid in the chemical industry addressed nitrous oxide (N_2O) emissions. Therefore, all figures of merit of the MACTool refer to the accounting of CO_2e emissions.

Chart 1 – Greenhouse gas emissions by industrial sector, 2005



Source: Adapted from CETESB (2013)

2.2.1 Marginal Abatement Cost Curve

The project's methodology is based on the so-called Marginal Abatement Cost Curve (MACC). The curve shows each technology with the total potential for reducing carbon dioxide equivalent (CO_2e) in the abscissas (x-axis) by cost in U.S. dollars of the ton of avoided carbon (USD/tCO_2) in the ordinates (y-axis). The potential is the sum of emissions avoided over the period of analysis. This study covers the period between 2014 and 2030. The area of each "step" of the curve reflects the total cost of the technology if its full reduction potential is reached, as shown in **Chart 2**.

It is important to point out that measures A, B and C, which show a negative MAC in Chart 2, do not actually have a zero or negative cost. They involve implementation and operating costs, which are lower than costs in the BS and, consequently, generate a negative incremental result.

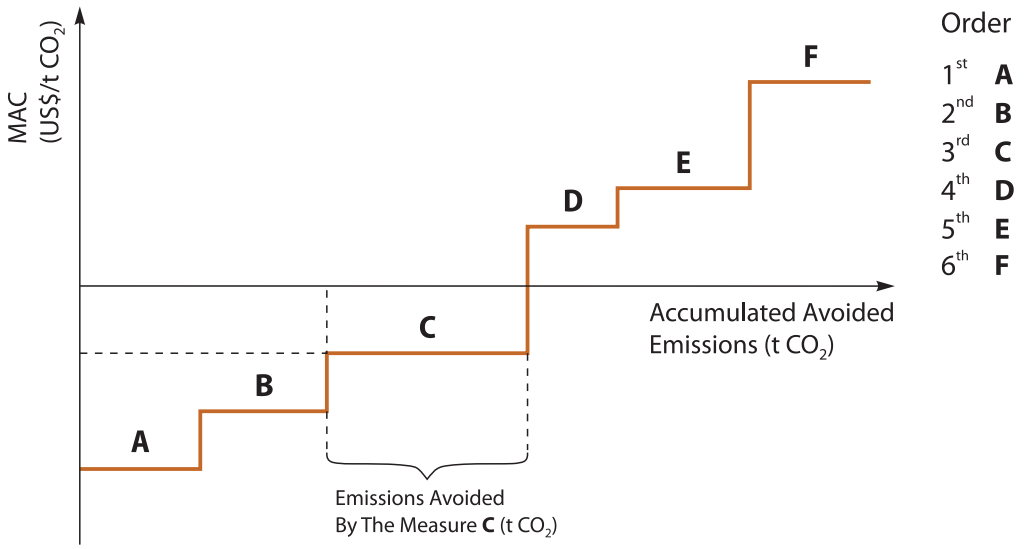
Producing this curve requires calculating the Marginal Abatement Cost (MAC) of each technology. The calculation was performed using the incremental approach, which is a cost-benefit analysis that compares values in both the BS and the LCS. Information such as the costs of deploying the technologies and their CO_2e emissions are essential to determine the

MACTool

The MACTool is used to analyzes input values for the construction of marginal abatement cost curves (MAC), providing cost-benefit comparisons between mitigation options and an estimate of the incentives needed to make them attractive, by calculating the break-even carbon prices (BECP). The tool also enables assessing the total investment needed to make the changes towards low carbon growth, and can be used to test possibilities by exploring sectors and responses to carbon prices (ESMAP, 2016).

As input parameters, users must specify in the MACTool at least one scenario for the future macroeconomic variables of interest, such as the price and future demand of fossil fuels, and provide scenarios considering the future inclusion of low carbon technologies and measures for a baseline and at least one emission reduction pathway (FAY, et al., 2015).

Chart 2 – Schematization of a Marginal Abatement Cost Curve



Source: Prepared by the authors (2019)

MAC of mitigation technologies. Depending on the case analyzed, the economic result may include costs and revenues, but in some cases only costs are considered. **Equation 1** represents a simplification of the approach used to determine the MAC.

Equation 1 – MAC calculation from the baseline and low carbon scenarios

$$\frac{USD}{tCO_2e} = \frac{OUTCOME_{Low\ Carbon} - OUTCOME_{Baseline}}{EMISSION_{Baseline} - EMISSION_{Low\ Carbon}}$$

Source: Adapted from Gouvello et al. (2010).

The economic result is the sum of the total annual costs calculated in terms of present values in relation to the year 2013.

To convert the future values of each project, the same discount rate was applied for all sectors, as seen in **Equation 2**.

More details on the MAC calculation can be found in Appendix B.

Equation 2 – Present value for flow of discounted future values

$$PV = \frac{FV}{(1+r)^{a_f - a_0}} + \frac{FV}{(1+r)^{a_f - a_0}} + ... + \frac{FV}{(1+r)^{a_f - a_0}}$$

Source: Prepared by the authors (2019)

Where:

VP	=	Present value of discounted future values at an annual discount rate	(USD)
VF	=	Future values that will be subject to a discount rate	(USD)
r	=	Annual discount rate	(%)
a_f	=	Future value year	(dimensionless)
a_0	=	Base year (2013)	(dimensionless)

2.2.2 Break-Even Carbon Price

The BECP is the price that the avoided ton of carbon should reach in the market in a carbon pricing system, to make the deployment of technology attractive to investors. The BECP is calculated based on an attractiveness rate (IRR Benchmark) that should corroborate the internal rate of return (IRR) expected by entrepreneurs for them to use the technology. This is different from the MAC Curve, in which the same discount rate is used for all the measures considered. Therefore, the BECP of the LCS

technology should provide an IRR equivalent to the attractiveness rate for its use to be convenient (GOUVELLO et al., 2010).

The result of the curve with the BECP is a graphical representation similar to the MAC Curve (Graph 2), with the abscissas indicating the emissions avoided by each measure and the ordinates indicating the BECP in USD/tCO_2. But instead of meaning the cost of the avoided ton of CO_2, this value means the minimum price at which the ton of CO_2 should be sold for investors to meet their return target. The BECP is calculated basically the same way as the MAC, with the particularity that not only costs but also avoided emissions are converted into present value (Equation 2). This is done because it is assumed that there is a price assigned to the avoided mass of carbon and thus the physical value is translated into a "discounted" value. That is, considering a positive discount rate, it would be as if the mitigated amount of emissions over the period in values for the reference year (2013) were less than the simple sum of the emissions avoided each year. Thus, it is possible to calculate the value of the ton of CO_2 avoided over the period, which allows the project's economic result to reach the attractiveness rate expected by investors. Both the PV and investment annualization[3] are calculated based on the sector attractiveness rate (IRR Benchmark).

It should be noted that there are two BECP results in the MACTool: one called BECP, which is not calculated incrementally, and the Incremental BECP. The simple BEPC is not incremental because it is not subtracted from the BS. The incremental BEPC, in turn, stems from the subtraction between the BS and LCS values. The incremental BEPC allows comparability with the MAC Curve result, so that any references to the BECP in the present study means the Incremental BECP calculated by the MACTool.

2.2.3 Wedge Graph

In 2004, Science magazine published the study entitled Stabilization Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies (PACALA; SOCOLOW, 2004) on the challenges of mitigating carbon emissions in the 21st century.

According to the study, the technology options that would avoid a doubling of preindustrial CO_2 concentration in the atmosphere in the next 50 years are already available and many are implemented somewhere at a full industrial scale. Therefore, solving the global climate issue would require expanding their use to maximize the emission mitigation potential.

The possibilities to limit atmospheric CO_2 concentration would prevent damaging climate change and could stabilize CO_2concentration at around 500 parts per million (ppm), or less than double the preindustrial concentration of 280 ppm. The CO_2 emission reductions necessary to achieve any such target depend on the emissions judged likely to occur in the period under consideration, the so-called BS emissions, as well as on the quantitative details of the stabilization target, and the future behavior of natural sinks. According to the study by Pacala and Socolow (2004), considering CO_2 alone for a stabilization corresponding to 500 ppm, emissions should be held at approximately 7 billion tons of carbon per year (GtC/year)[4] for the 50 years following the study.

3. Annualization is an operation that allows to determine the annual value of a given investment based on an interest rate and the useful life of the acquired asset, which makes up the Capital Recovery Factor (CRF).

4. 7 GtC correspond to 25.7 tons of CO_2. While quantification of carbon fluxes is traditional in carbon cycle diagrams, emissions are generally accounted for based on carbon dioxide (CO_2).

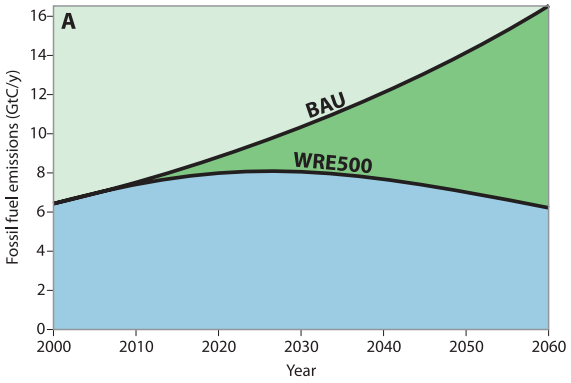
In the study by Pacala and Socolow (2004), baseline and stabilization emissions of atmospheric CO_2 concentrations, which are shown in **Figure 3** for the next 50 years, were idealized as a perfect triangle (**Figure 4**), where stabilization (or LCS) is represented by a fat trajectory of emissions at 7 GtC/year, and the BS is represented by a trajectory ramping up to 14 GtC/year in 2054[5]. The triangular stabilization located between the stable LCS and the BS, removes exactly one third of BS emissions. To maintain the focus on technologies with substantial reduction potential for 2054, the triangle was divided into 7 wedges, in which each wedge represents an activity for the reduction of GHG emissions, starting from zero — represented by the years of the study until 2054, showing a linear growth up to a total reduction of 1 GtC (3.67 $GtCO_2e$) in 50 years (i.e. the wedge area corresponds to 1 GtC, and it is important to understand that each wedge represents an effort beyond what would occur in the BS trajectory).

Wedges can be achieved from energy efficiency, from the decarbonization of the supply of electricity and fuels (by means of fuel shifting, carbon capture and storage, nuclear energy, and renewable energy) and from biological storage in forests and agricultural soils. Achieving one wedge often interacts with achieving another wedge and requires some price trajectory for carbon, the details of which depend on many assumptions, including future fuel prices, public acceptance, and cost reductions through learning about emerging technologies.

In general, energy efficiency and conservation offer the greatest potential to provide wedges. In the study by Pacala and Socolow (2004), four options were presented for the efficiency and conservation category: fuel economy by improving vehicle autonomy; reduced reliance on cars; more efficient buildings; and improved power plant efficiency. As for decarbonization of electricity and fuels, the following options were presented: substituting natural gas (NG) for coal; storage of carbon captured (CCS) in power plants; storage of carbon captured in hydrogen plants; storage of carbon captured in synfuel (synthetic fuel) plants; nuclear fission; wind electricity; photovoltaic electricity; renewable hydrogen; and biofuels.

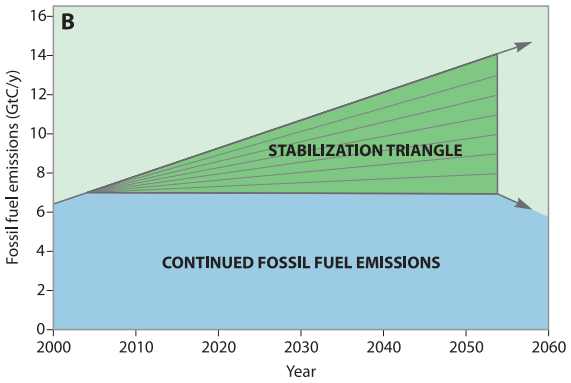
Sectoral wedge graphs and one wedge graph consolidating the mitigation potential of all the measures addressed in the analysis were prepared for the study.

Figure 3 – Emissions and stabilization



Source: Pacala e Socolow (2004).

Figure 4 – Emissions and stabilization triangle



Source: Pacala e Socolow (2004).

5. In its latest report the IPCC estimated that emissions from fossil fuel combustion and cement production in 2012 were around 7.8 ± 0.6 GtC (IPCC, 2013).

2.2.4 Investment charts

Investment charts are another relevant result in the MACTool. From investment results, investors in the LCS technology can, for example, assess the need to both leverage capital and get financing from banks.

The MACTool has four categories to present investments of a given technology in the LCS: (i) investment cost chart; (Ii) incremental investment cost chart; (iii) investment intensity chart; and (iv) incremental investment intensity chart.

2.2.4.1 Investment cost chart

The investment cost chart shows the total investment cost of each LCS technology for the period 2014–2030, in USD million.

2.2.4.2 Incremental investment cost chart

The incremental investment cost chart shows the difference between the total investment costs of each LCS technology in relation to the total investment in the BS for the period 2014–2030, in USD million.

2.2.4.3 Investment intensity chart

The investment intensity chart shows the investment cost per ton of CO_2 (USD/tCO_2) of LCS technologies. It is the ratio of the total cost of investment to the total amount of CO_2 avoided in the period 2014–2030.

2.2.4.4 Incremental investment intensity chart

The same result as in the previous item. However, this is done incrementally by subtracting the investment in the BS from the LCS. Among the four investment charts, the result of the incremental investment intensity in USD/tCO_2 is the one that most closely resembles the MAC calculation and, therefore, enables direct comparisons with the MAC Curve.

2.3 EMISSION FACTORS

Emission factors (EF) are essential to estimate the evolution of emissions in the BS and of technologies in the LCS and were used to estimate the amounts of GHG emissions according to **Equation 3**.

In general, the EFs and GHG estimation methods used in the study are industry-specific and have as their main source the IPCC guidelines and various industry-specific publications. In relation to energy emissions, the study established factors to be used in the estimates for all industrial sectors, which are described below.

Equation 3 – Estimate of greenhouse gas emissions

$$GHG\ emission = \text{activity data} * \text{emission factor}$$

Source: IPCC (2000)

For most fossil fuels, the values used were those provided by the IPCC (1996) and IPCC 2006 (Gomez et al., 2006), and used by BRAZIL (2006) in the national inventory and by CETESB (2011) in the State Communication. However, some EFs such as for electricity generation and use of biomass were determined using other methods and other sources, which will be detailed later.

2.3.1 Emission factor for fossil fuels

The EFs for fuels were determined according to **Equation 4**.

Fuel carbon contents, oxidation fractions and conversion to CO_2 are shown in Table 1, which also presents the EFs obtained from this information.

Equation 4 – Calculation of the CO_2 emission factor for fuels

$$\text{Emission factor} = \text{Carbon content} * \text{Oxidation fraction} * \text{Conversion to } CO_2$$

Source: Adapted from Gomez et al. (2006)

The values in **Table 1** were used in the preparation of CETESB's *Inventário de emissões antrópicas de gases de efeito estufa diretos e indiretos do Estado de Sao Paulo* (*Inventory of anthropogenic emissions of direct and indirect greenhouse gases of the State of Sao Paulo*), published in 2011. The calculation methodology used at the time was published in the *Relatório de referência das emissões de CO_2 por queima de combustíveis no Estado de Sao Paulo, 1990 a 2008: Abordagem de referência* (*Baseline report of CO_2 emissions from fuel combustion in the State of Sao Paulo, 1990 to 2008: A baseline approach* – CETESB, 2010), published for public consultation on CETESB's website between 2010 and 2013. The primary source of EFs was the document published by the IPCC, *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (GOMEZ et al., 2006). However, the amounts in the 1996 guide (IPCC, 1996) were used for refinery gas (GR) and petroleum coke as well as for national and state inventories.

Table 2 shows a comparison between the average amounts in the IPCC (GOMEZ et al., 2006) and those used by CETESB (2010).

The analysis of **Table 2** allows to conclude that for fuels: NG, diesel fuel, fuel oil (FO), liquefied petroleum gas (LPG), kerosene, and petroleum coke, the difference is negligible. On the other hand, the EF of refinery gas (RG) used by CETESB according to the IPCC (1996) is 13% higher when compared to the 2006 IPCC guide. The most conservative EF was used for RG and petroleum coke (IPCC, 1996).

Table 2 – Comparison between emission factors used by CETESB (2010) and the IPCC (GOMEZ et al., 2006)

Energy sources	CETESB	IPCC	Difference
	($kgCO_2/TJ$)	($kgCO_2/TJ$)	(%)
NG	55,820	56,100	0.5
Diesel fuel	73,326	74,100	1.1
Fuel oil	76,593	77,400	1.1
PLG	62,436	63,100	1.1
Kerosene	70,785	71,900	1.6
RG	66,066	57,600	– 12.8
Petroleum coke	99,825	97,500	– 2.3

Source: Prepared by the authors (2019) based on CETESB (2010) and Gomez et al. (2006)

Table 1 – Fossil fuel emission factors

Energy sources	Carbon content	Oxidation fraction	Conversion to CO_2	Emission factor
	(tC/TJ)	(%)	(dimensionless)	(tCO_2/GJ)
Natural gas	15.3	100%	3.67	0.0558
Diesel fuel	20.2	99%	3.67	0.0733
Fuel oil	21.1	99%	3.67	0.0766
PLG	17.2	99%	3.67	0.0624
Kerosene	19.5	99%	3.67	0.0708
RG	18.2 (1)	99%	3.67	0.0661
Petroleum coke	27.5 (1)	99%	3.67	0.0998

Source: Prepared by the authors (2019) based on Gomez et al. (2006)
(1) Based on IPCC amounts (1996)

2.3.2 Electricity emission factors

In this project, the factors for Clean Development Mechanism (CDM) projects and inventories were used regarding electricity emission factors. According to the Ministry of Science, Technology and Innovation (MCTI), CDM factors are intended to estimate carbon reduction for projects that provide electricity to the grid (e.g. photovoltaic modules connected to the grid), quantifying the emission displaced at the margin (MWh), i.e., considering that generating or saving 1 megawatt-hour means avoiding GHG emissions considering only the plants that make up the operation and expansion margin of the electric system, whose EF is higher than the average of the EF taking into the park operating in the country. This same approach was used in the Low Carbon Study for Brazil (GOUVELLO et al., 2010).

The factor for inventories is intended to represent all the technologies used in electricity generation in the country, estimating the emissions that are being generated at a given moment from electricity consumption. Considering that the Brazilian matrix is made up largely of renewable energies, the EF for inventories is lower than that used in CDM projects. **Box 2** shows the measures in which the electricity EF for CDM and the electricity EF for inventories were used.

There is a unit difference in the order of magnitude of the two types of factors. The average for CDM emission factors for the period 2006 to 2014 was 0.4226 tCO_2/MWh, while the average for inventories over the same period was 0.0569 tCO_2/MWh (about 8 times smaller). **Chart 3** shows the evolution of the two factors in the period. The years 2013 and 2014 were chosen for the analysis because they are relatively stable compared to previous years, besides the fact that the base year for the project analysis is 2013.

2.3.2.1 Electricity emission factor for CDM projects

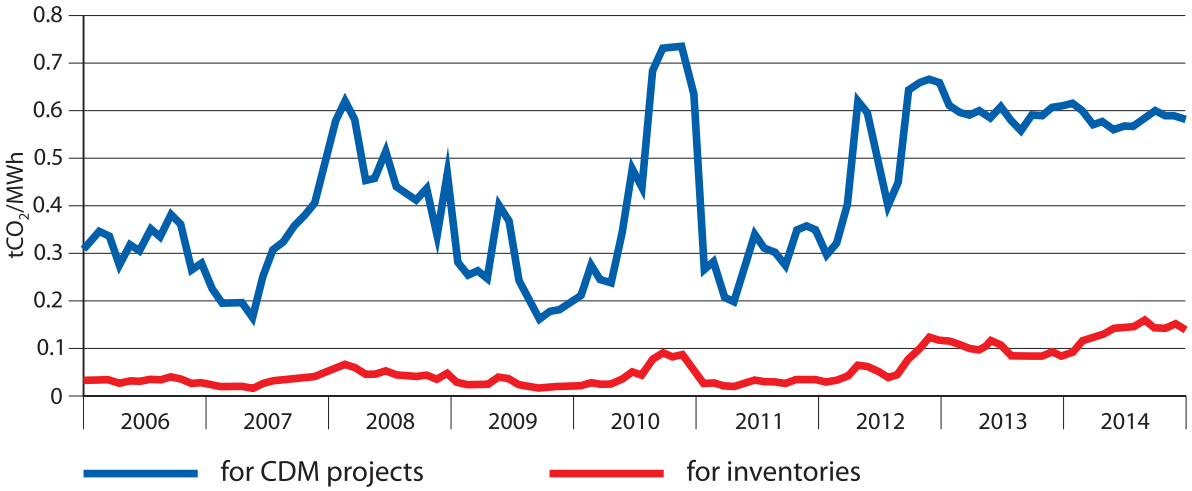
The CDM EF was considered for measures that provide emission reduction through electrical efficiency or that allow the introduction of energy in the grid through cogeneration, since according to the MCTI (BRAZIL, [2015?]) it is an algorithm widely used to quantify future contributions in terms of reduction of CO_2 emissions in relation to a BS.

Box 2 – Low-carbon measures and electricity emission factor used

Sector	Electricity EF for CDM	Electricity EF for inventories
Chemical	■ Plant lighting using LED lamps ■ More efficient electric motors ■ NG Cogeneration	—
Lime	—	■ Replacement of Azbe kiln with Maerz kiln using biomass in natura ■ Replacement of Azbe kiln with Maerz kiln using torrefied biomass
Steel	■ Preheating and continuous feed ■ Direct current furnace	■ TGRBF-MDEA
Cement	—	■ Increase of filler content in cement products ■ Ready-mix concrete (1) ■ Ready-mix concrete mixer (1) ■ Industrialized mortar (1)

Source: Prepared by the authors (2019) based on Vogellar (2015b; 2015c), Punhagui and Oliveira (2016), Fanti and Souza (2016), Strumpf and Kurimori (2015).
(1) Measures from the construction area (Appendix A)

Chart 3 – Comparison between emission factors for Clean Development Mechanism projects and inventories, 2006–2014



Source: Prepared by the authors (2019) based on MCTI data (BRAZIL, [2015?]).

Among fossil sources, which are more carbon emission-intensive, used in the generation delivered to the national interconnected system, it is observed that the shares of coal and FO were 2.6% and 4.4% respectively in 2013 (EPE, 2014). These sources can be replaced by renewable sources in electricity generation.

The average emission factor for CDM was equivalent to 0.5884 tCO_2/MWh. This value was entered in the MACTool for the years 2014 to 2030. The tool calculates electricity emissions according to Equation 3, including the network loss factor (Chart 6), pursuant to Equation 20.

Considering that the EF of NG is 0.2 tCO_2/MWh (0.0558 tCO_2/GJ), the CDM EF used implies an efficiency of approximately 34% for the conversion technology of the thermal energy from NG into electricity.

Depending on the fuel used by the new thermoelectric plants, the CDM EF can increase; however, a fixed amount is being used over the period.

2.3.2.2 Electricity emission factor for inventories

This study uses the emission factors of inventories for measures that are not related to electricity generation or conservation, but that use it for industrial production processes.

The emissions from each industrial technology are assessed by inventory through the sum of each CO_2 emission variable, including electricity consumption. According to the MCTI (BRAZIL, [2015?]), in this case the EF for inventories should be used when the goal is to quantify electricity emissions that are being generated at a given time. It therefore serves for general, corporate or other types of inventories.

In the MACTool, electricity emissions using the inventory factor were calculated separately, added to the other emission sources and introduced year by year in the guide for each technology. The factor used in these cases was 0.1335 tCO_2/MWh, which corresponds to the average emission in 2014. MCTI (BRAZIL, [2015?]).

2.3.3 Biomass emission factor

For the purposes of the project, carbon dioxide (CO_2) emissions from burning biomass (firewood, sugarcane bagasse, charcoal) are equal to zero. It is assumed that the CO_2 emitted during combustion is reabsorbed by photosynthesis during the growth of the biomass (plant) that is grown on the site from which the previous biomass has been removed (DONG et al., 2006). Therefore, from the point of view of the carbon cycle a balance occurs and net emissions are neutral, as shown in **Figure 5**.

In this study, the following types of biomass were used: (i) reforestation wood for Maerz kiln technologies in the lime industry and for the substitution of fossils in the chemical industry; (ii) ethanol[6] for bioethene production; (iii) wood pellets; and (iv) refuse-derived fuel (RDF) in the substitution of petroleum coke in the cement industry. In all these cases, an FE equal to zero was used.

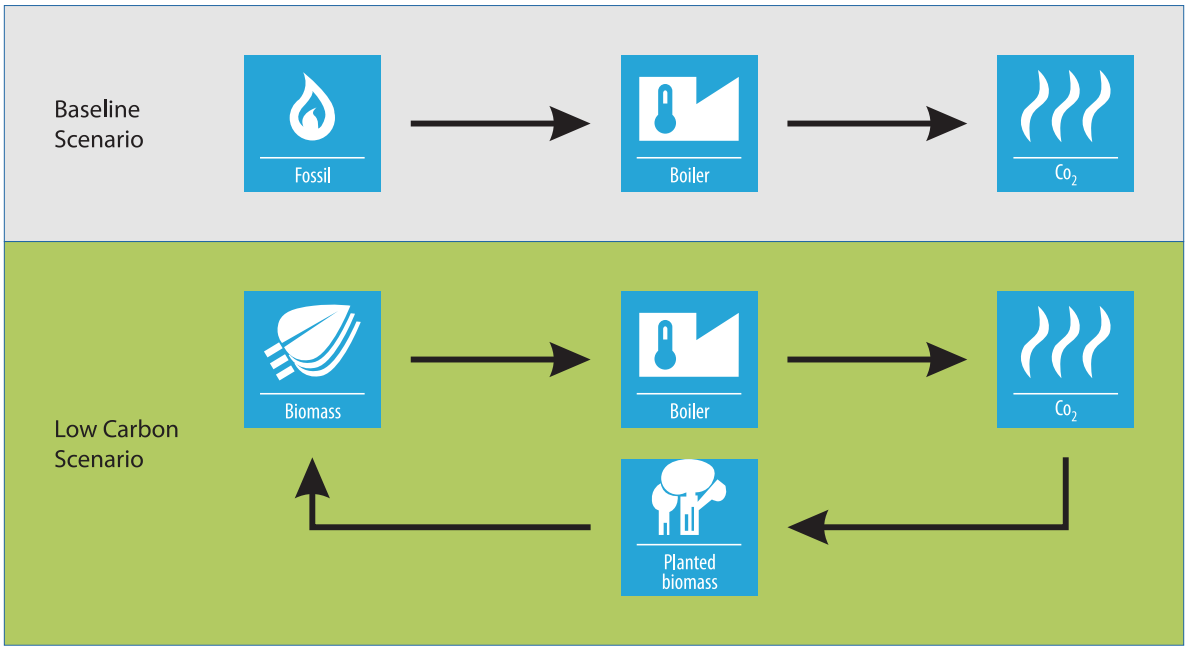
2.4 SOURCE OF CO_2 EMISSIONS: PROCESS AND ENERGY

CO_2 and other GHG emissions were separated in this study according to their origin within each sector. The study considered GHG emissions from industrial processes, which include energy consumption by the industrial sector. Emissions from the consumption of materials were also considered (Appendix A).

2.4.1 Process emissions

By process we mean GHG released in the manufacture of the product, i.e., through chemical reactions of the raw material for obtaining the final product. The CO_2 released in lime calcination (CaO) and nitrous oxide (N_2O) released by reagents in the chemical industry are examples of process emissions. Technologies to mitigate emissions from this source involve methods such as CCS or the replacement of the material

Figure 5 – Neutral emissions from biomass use



Source: Prepared by the authors (2019) based on DONG et al. (2006)

6. It should be noted that in the case of bioethene, ethanol is used as raw material and not as an energy source.

with substances that release less GHG in chemical reactions inherent in the processes.

In fact, of the three origins, process emissions are the most challenging from the standpoint of mitigation through measures in the LCS because, in general, it is something intrinsic to the chemical composition of reagents. Thus, the mitigation of these emissions depends on technologies that substitute or streamline the use of intensive inputs in GHG emissions.

2.4.2 Energy emissions

In the case of emissions from energy consumption, CO_2 is released by the burning of fuels to release the thermal energy required for industrial activities. GHG emissions also occurs in electricity generation either by thermoelectric plants (burning of fossil fuels such as NG or coal) or by hydroelectric plants (decomposition of flooded vegetation cover and other indirect sources). These emissions can be mitigated by introducing renewable sources such as biomass or even municipal waste, or by using technologies that increase energy efficiency (thermal or electric), thereby reducing fuel and electricity consumption and, consequently, carbon dioxide emissions.

The increase in energy efficiency, particularly, is attractive for industries, as in addition to reducing GHG emissions it can lead to an economic gain by reducing fuel or electricity consumption costs.

2.5 CURRENCY

The currency used in the analysis and results was the US dollar. The dollar to real (Brazilian currency) exchange rate used by the project was an average value taken from the National Energy Balance (BEN) (EPE, 2014), which presents the average sale price of the US currency.

For years prior to 2013, the corresponding rate was used for each year of the same table. These historical values were considered for the analysis of historical prices and for the projection of cost scenarios. When prices were in Real, like the historic price of firewood, historical exchange rate values were applied in the conversion to US dollar.

In the analysis performed, the base year considered was 2013 (2013 values) and the exchange rate for 2013 was used, i.e., 2.16 R$/USD. This rate was standardized for all sectors in calculations using conversion between the two currencies.

2.6 ENERGY PRICE SERIES

In the MACTool, energy prices from all sources can be obtained for any year by comparing the price of the energy source and the price of oil, or they can be included independently of the oil as additional prices. The choice of the comparison factor is reinforced by the fact that any energy carrier[7] can have a substitute produced from oil. Thus, the series of oil prices is used as a reference for determining the prices of other energy sources.

For standardization purposes, a relationship was initially established between the prices of all fuels and the price of a barrel of Brent oil (crude oil price). These factors, coupled with Brent oil price projections are used to estimate fuel prices in the future. Although electricity is also an energy carrier, we chose to perform a separate analysis due to the structure of the tool. Therefore, electricity prices are not directly related[8] to the projection of oil prices.

7. Energy source.
8. In the case of electricity generation/conservation measures, the price of NG is included in the cost of energy for electricity generation and is therefore indirectly related to the price of electricity.

Carbon Capture and Storage

Although it is still a costly and incipient technology, CCS has been considered one of the options to mitigate fossil CO_2 emissions in the lime industry in the future.

Regarding this technology, the Special Report on Carbon Dioxide Capture and Storage (SRCCS) (2005) was developed in 2005, addressing applications, concepts, possibilities, costs and implications. The document was prepared by Working Group III in response to an invitation from the United Nations Framework Convention on Climate Change (UNFCCC) at its 7th Conference of the Parties (COP 7) held in Marrakesh, Morocco, in 2001.

According to the report, CO^2 capture and storage (CCS) is a process that consists of separating CO^2 from the atmosphere or from an emission source, transporting it to a long-term storage and isolation site. The technology should be considered an option in the portfolio of mitigation and actions to stabilize the atmospheric GHG concentration of GHG (IPCC, 2005).

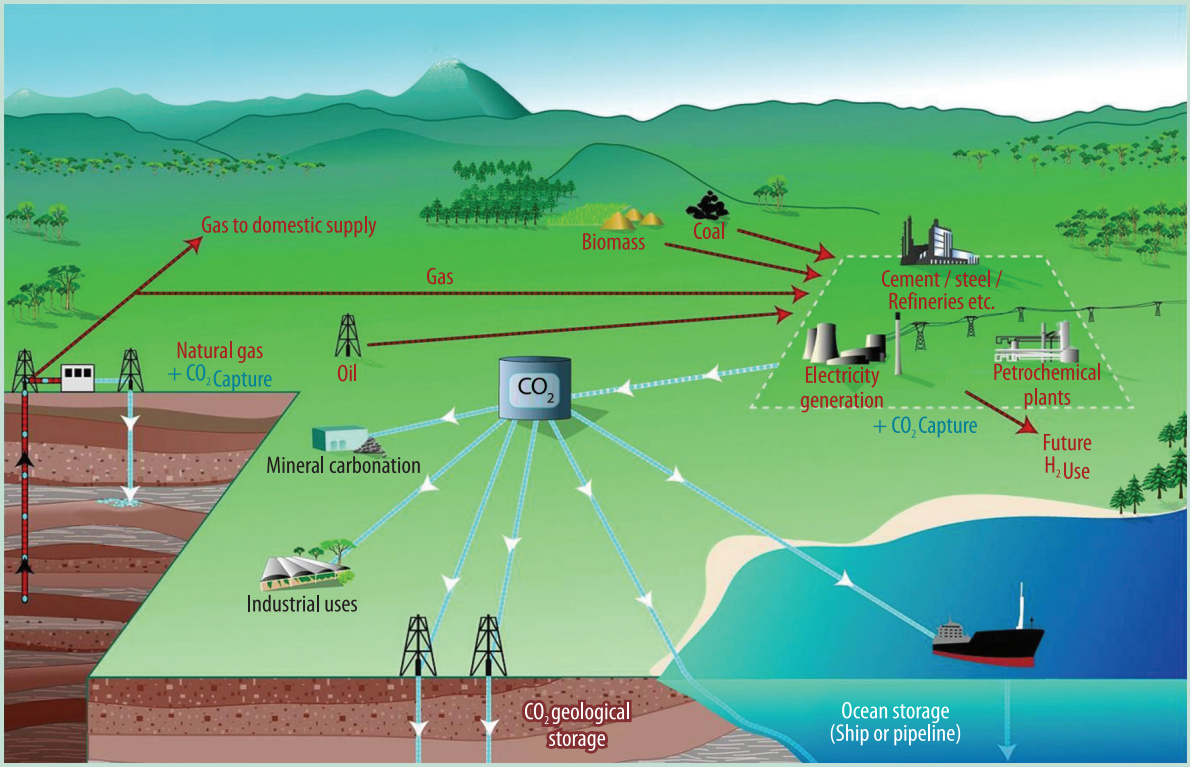
The captured CO^2 is compressed and transported for storage in geological formations, in the ocean or for use in industrial processes, as shown in Figure 6.

CO_2 storage in geological formations (Figure 7) uses many of the same technologies developed by the oil and gas industry.

CO_2 can be stored in oil and gas reservoirs, coal seams and deep geological formations, as well as in the oceans, by direct release in a water column or underground layers, and stored by industrial fixation in inorganic carbonates (IPCC, 2005).

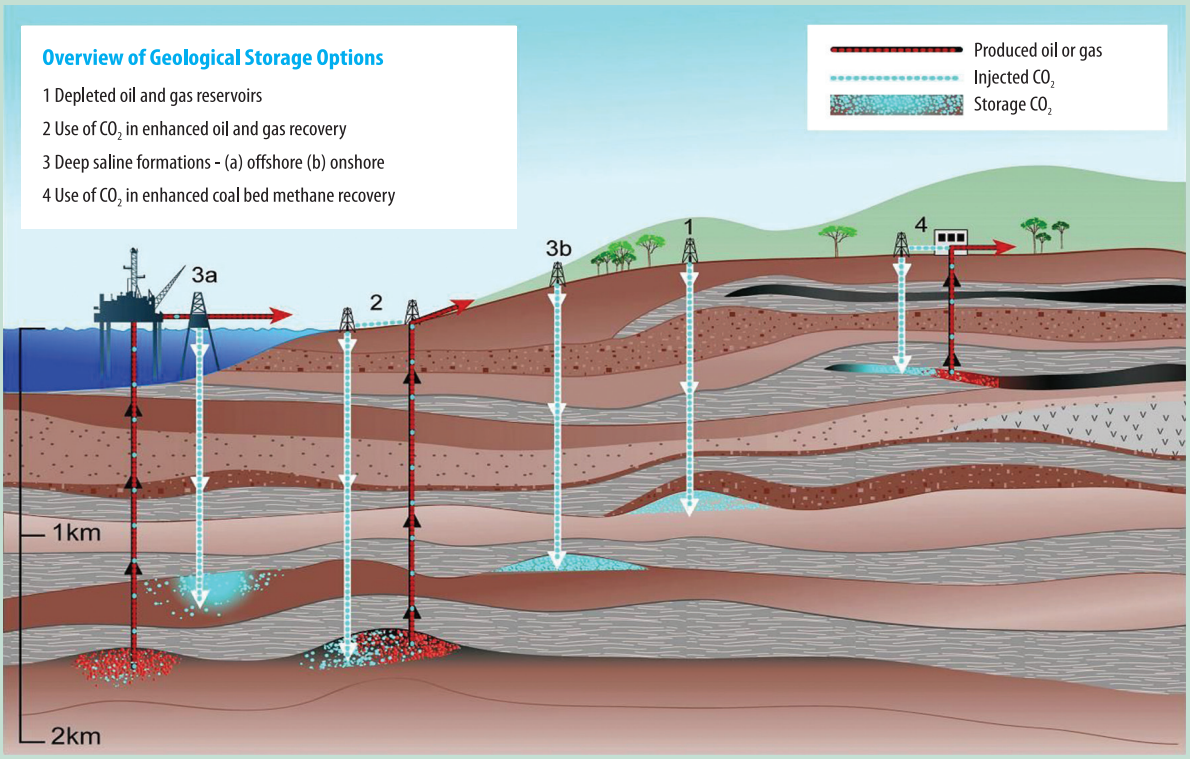
CO_2 storage in deep saline formations (Figure 7) uses many of the same technologies developed by the oil and gas industry.

Figure 6 – Schematic diagram of a carbon capture and storage system – Possible sources and storage options



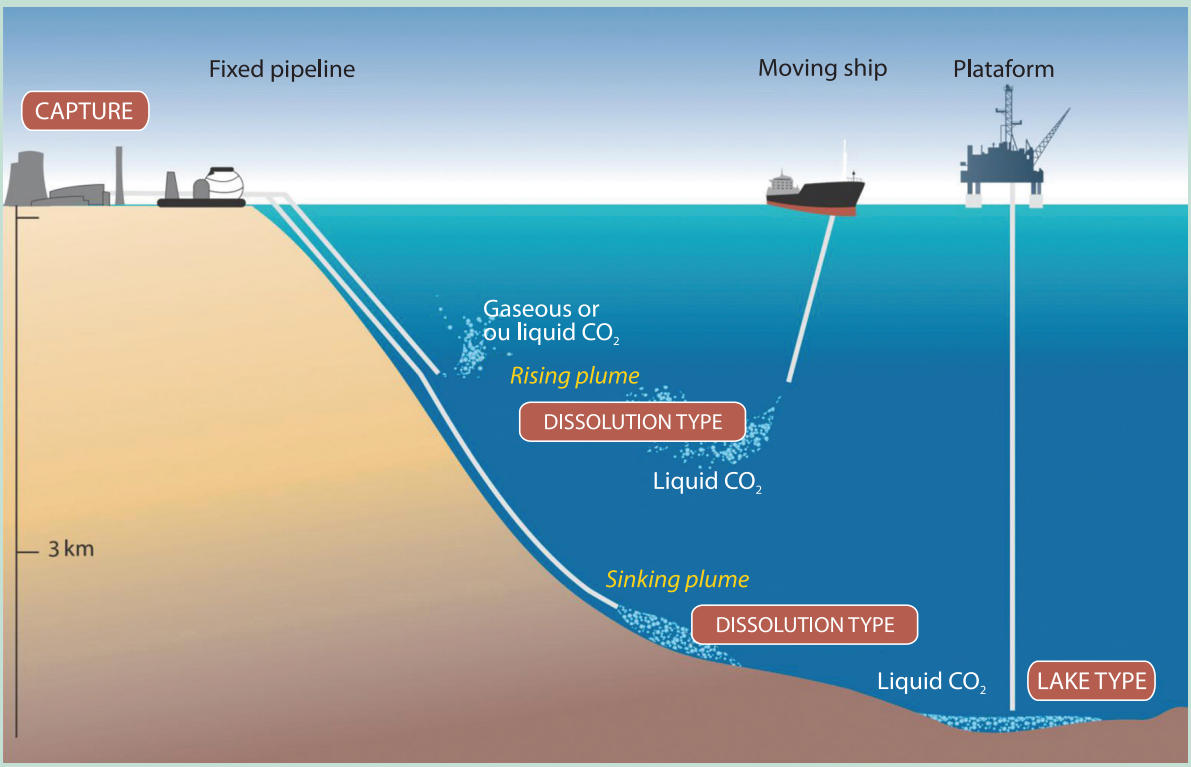
Source: IPCC (2005).

Figure 7 – Carbon capture and storage: deep geological formations



Source: IPCC (2005).

Figure 8 – Carbon capture and storage: oceans



Source: IPCC (2005).

2.6.1 Brent oil price

The price of a barrel of oil was projected based on Brent in US dollars per barrel instead of on the West Texas Intermediate (WTI) suggested in the MACTool.

According to a study released by the US Energy Information Administration of the US Department of Energy (EIA, 2014c), the price of a Brent oil barrel is an international reference and more relevant than the price of the WTI, which is a national reference for the US market to determine the prices of oil products. Gasoline is a commodity traded globally and its prices are strongly correlated among the global spot markets. Although the present study focuses on the State of Sao Paulo, we believe that the same consideration applies to both the domestic and state markets.

Brent and WTI are two terms that usually accompany oil prices. They indicate the origin of the oil and the market where it is traded. Brent oil has this name because it was extracted from a Shell platform called Brent. However, Brent currently designates all the oil extracted in the North Sea and traded on the London Stock Exchange. The Brent price is a reference for the European and Asian markets. WTI oil, in turn, comes from Texas, which is the main oil-producing region in the United States. WTI oil is sold by West Texas traders and traded on the New York Stock Exchange (WOLFFENBÜTTEL, 2005).

The prices used for Brent Oil projections were taken from the annual energy overview report published in April 2014 by the EIA (2014a). These prices are compiled in **Table 3**.

Table 3 – Brent projections for the period 2011 to 2030

Year	Brent price (USD/barrel)
2011	113,24
2012	111,65
2020	96,57
2025	108,99
2030	118,99

Source: EIA (2014a)

Equation 5 – Calculation of Brent oil price (2013–2030)

$$B_t = B_{t-1} + [(B_{tF} - B_{t0})/p]$$

Source: Prepared by the authors (2019)

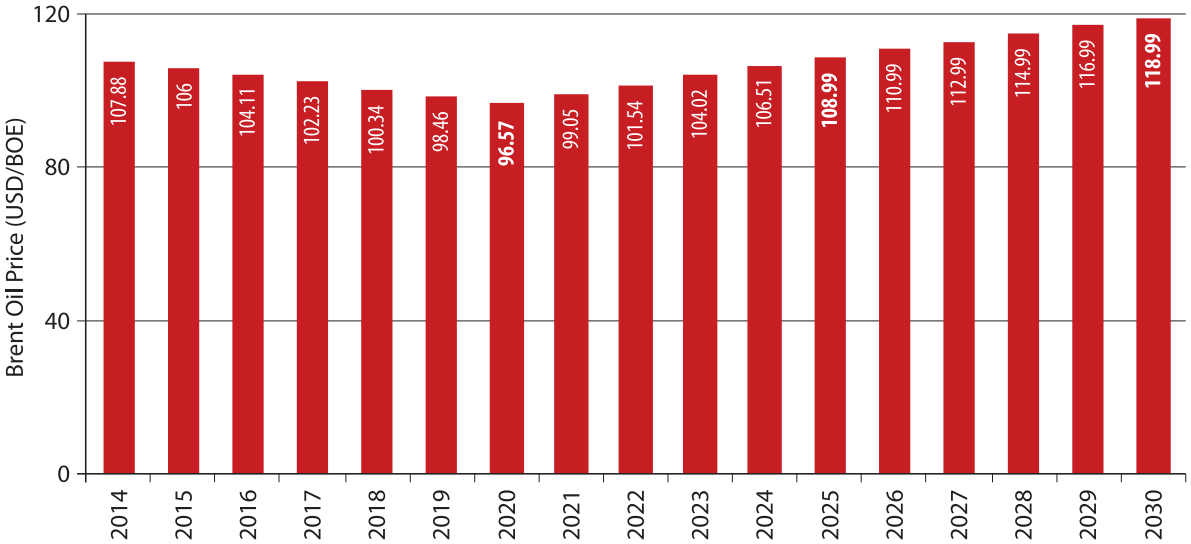
Where:

t	=	year of interest	(year)
B_t	=	Brent price	(USD/barrel)
B_{tF}	=	Brent price in final year	(USD/barrel)
B_{t0}	=	Brent price in initial year	(USD/barrel)
p	=	period = final year – initial year	(year)

Brent data were presented in **Table 3** for the years 2011, 2012, 2020, 2025 and 2030. An interpolation was performed to obtain year-to-year prices, as described generically by **Equation 5**.

After applying the interpolation for each segment (2013–2019; 2021–2024 and 2026–2030), the following projected prices for Brent were obtained (**Chart 4**).

Chart 4 – Annual projection for Brent oil prices, 2013 to 2030



Source: Prepared by the authors (2019) from Table 3 e Equation 5.
Note: The years of 2020, 2025 and 2030 are data. The others are projections.

2.6.2 Energy price calculated as a fixed proportion of Brent price

To aggregate all mitigation measures of the various sectors into a single curve, it was necessary to establish consistency regarding fuel prices considered throughout the analyzed period, so that they would be the same for all calculations. Thus, a correlation factor with the oil price was determined for each energy carrier.

The goal of this factor was to obtain the correlation between the Brent price in dollars per barrel of crude oil (USD/BOE[9]) and the current price of energy (USD/BOE or USD/TOE[10]). Most energy prices in the MACTool are in (USD/TOE). The correlation index was determined according to **Equation 6**.

The Brent price time series (crude oil price in USD/barrel) was taken from the EIA website (2014b). They correspond to the "Europe Brent Spot Price FOB", whose data were made available on an annual basis between 1987 and 2013.

The Current Prices of Energy Sources (presented in USD/BOE) were obtained from

Equation 6 – Calculation of equivalence factor

$$R = \frac{P_e * F}{P_b}$$

Source: Prepared by the authors (2019)

Where:

R (1)	=	fuel price in relation to oil barrel	(BOE/TOE) or (BOE/BOE)
P_e	=	current price of energy source	(USD/TOE) or (USD/BOE)
P_b	=	Brent price	(USD/BOE)
F	=	BOE to TOE conversion factor (2)	7.0369 (BOE/TOE)

(1) The equivalence factor unit for entry into MACTool depends on the fuel. Thus, as it was not possible to standardize all fuels for the same unit, they were converted according to the demand of the tool.
(2) The conversion factor was only used for prices taken from BEN (EPE, 2014) that are presented in USD/boe. For the other fuels, which come from other sources, this factor was not used because the prices were converted directly to USD/toe.

9. The barrel of oil equivalent (BOE) is an energy measurement unit equivalent to the energy contained in a barrel of oil or 6.383 GJ. It should not be mistaken for the "barrel", which is a volume unit (generally crude oil) equal to 158.98 liters.
10. The ton of oil equivalent (TOE) is also an energy measurement unit equivalent to the energy contained in a ton of oil or 41.8 GJ.

BEN (EPE, 2014). Conversion factors were also obtained from BEN. The conversion was performed according to Equation 6.

Some fuels in the MACTool are already in USD/BOE. Thus, the formula for calculating their relation to oil does not involve the conversion factor shown in Equation 6, which represents the energy equivalence between the TOE and the BOE.

2.6.2.1 Price of firewood

The price of firewood was obtained from the time series provided by the Center for Advanced Studies in Applied Economics of the Luiz de Queiroz School of Agriculture (CEPEA/ESALQ), University of Sao Paulo (USP). They refer to the monthly average price of eucalyptus wood (with bark) in the State of Sao Paulo cut and stacked on the farm.

The price of firewood is shown in Brazilian reals per cubic meter, or stere[11] (R$/m^3 st), and corresponds to the top of the tree or tree branches of standing forests, plus the cost of cutting and stacking in the patio for loading in trucks, vans or tractors. The loading cost was not included in the means of transport.

The original values of the time series were adjusted. For that, the mean value of the series was used and the average for each year was obtained based on these values. It should be noted that the average for 2002 was calculated from July to December and for 2014 from January to November. In the remaining years (2003 to 2013), the average was calculated between the months of January and December, since month-by-month data was available.

According to the BEN (EPE, 2014), the density of commercial firewood is 390 kg/m^3 st, which corresponds to the commercial eucalyptus firewood. The monetary conversion rate from Brazilian Real to US Dollar is the average commercial dollar value for each year of calculation (EPE, 2014).

Equation 7 was used for the conversion of R$/m^3 st to USD/TOE. The input values in the MACTool referring to the price of firewood energy are shown in USD/TOE (dollars per ton of oil equivalent). Since the data provided by CEPEA/ESALQ (2014) is in R$/m^3 st, these values had to be converted.

Equation 7 – Price of firewood

$$F_p = P * \frac{1}{D} * \frac{1}{F} * \frac{1}{R} * 1000$$

Source: Prepared by the authors (2019)

Where:

F_p	=	final price of firewood	(USD/TOE)
P	=	original price of firewood	(R$/m^{3}st) (CEPEA/ESALQ, 2014)
D	=	density of firewood	390.00 (kg/m^{3}st) (EPE, 2014)
F	=	conversion factor of firewood from t to TOE	0.31 [TOE/t] (EPE, 2014)
R	=	Brazilian Real to US Dollar exchange rate in the respective year	(R$/USD) (EPE, 2014)

The values shown in **Table 4** for the price of firewood were obtained by applying the formulas.

The prices on **Table 4** were used to calculate the equivalence factor related to Brent according to **Equation 6**.

11. Stereo (st) is a unit of measure that represents a cubic meter of uneven and stacked wood, considering the gaps between the pieces.

Table 4 – Annual average price of eucalyptus firewood in the State of Sao Paulo

Year	Average annual price (USD/TOE)
2004	70.97
2005	105.64
2006	134.76
2007	153.79
2008	178.55
2009	173.68
2010	197.44
2011	216.33
2012	189.03
2013	172.96

Source: Prepared by the authors (2019) based on CEPEA/ESALQ (2014, unpublished information [excel file]) and Equation 7.

2.6.2.2 Price of naphtha

The primary data on naphtha prices were taken from the time series available in the QUOTENET database (FINANZEN.NET GMBH, 2016). A series from the period 2005 to 2013 was used to generate the equivalence factor. It should be noted that there is a lack of data: for 2005 data is available only from October to December; for 2006, from January to May; and for 2007, only for November and December. The arithmetic average of naphtha prices for each year was calculated from these primary data.

Since the primary source price unit is in US dollars per ton (USD/t) and the MACTool requires the unit to be in US dollars per barrel of oil equivalent (USD/BOE), **Equation 8** below was used to convert the units.

The prices in US dollars per BOE are shown in **Table 5**. These values were used to find the ratio factor between the prices of naphtha and petroleum.

The prices on **Table 5** were used to calculate the Brent-related equivalence factor according to **Equation 6**.

Equation 8 – Price of naphtha

$$F_p = P * \frac{1}{H} * F$$

Source: Prepared by the authors (2017)

Where:

F_p	= final price of naphtha	(USD/BOE)
P	= original price of naphtha	(USD/10^3 kg)
H	= naphtha heating value	11,320 (kcal/kg) (EPE, 2014)
F	= Kcal to BOE conversion factor	7.03×10^6 (kcal/BOE) (EPE, 2014)

Table 5 – Annual averages of naphtha prices for the State of Sao Paulo

Year	Price (USD/BOE)
2005	63.97
2006	70.21
2007	100.55
2008	92.62
2009	66.91
2010	89.64
2011	115.35
2012	113.30
2013	112.29

Source: Prepared by the authors (2019) based on QUOTENET (FINANZEN.NET GMBH, 2016) and Equation 8.

2.6.2.3 Price of petroleum coke

Petroleum coke is the fuel used in the lime[12], chemical and cement industries among others. Primary data were taken from AliceWeb (BRAZIL, 2016), a database with information on foreign trade, through free registration.

12. Except for the case of Sao Paulo, where reforestation wood is used (FREITAS; VOGELAAR, René; VOGELAAR, Renato, 2017a).

The data are presented as the total amount paid for importing the product (petroleum coke, in US dollars) and the total quantity of the product (in kilograms) imported in a selected period. Annual averages were calculated from 2004 to 2013. **Equation 9** was used to convert the database to US dollars per ton of oil equivalent (USD/TOE).

The final prices of petroleum coke used to calculate the equivalence factor are shown in **Table 6**.

The prices on Table 6 were used to calculate the Brent-related equivalence factor according to Equation 6.

Equation 9 – Price of petroleum coke

$$F_p = \frac{P}{Q} * \frac{1}{H} * F$$

Source: Prepared by the authors (2019)

Where:

F_p	=	final price	(USD/TOE)
P	=	total price of petroleum coke imports in the year	(USD)
Q	=	total quantity of petroleum coke imports in the year	(kg)
H	=	heating value of petroleum coke	8.500 (kcal/kg) (EPE, 2014)
F	=	Kcal to TOE conversion factor	10^7 (kcal/TOE) (EPE, 2014)

Table 6 – Annual averages of petroleum coke prices

Year	Price
	(USD/TOE)
2004	21.67
2005	34.07
2006	48.33
2007	69.15
2008	106.83
2009	63.14
2010	117.35
2011	166.67
2012	113.86
2013	108.82

Source: Prepared by the authors (2019) based on BRAZIL (2016) and Equation 9.

2.6.2.4 Price of Refinery Gas

The prices for RG were determined, as per consultation with the chemical sector specialist, based on the NG (EPE, 2014) price and the respective heating values of each gas. Equation 10 shows this relation.

Table 7 presents the prices for RG obtained from NG and used to calculate the equivalence factor:

The prices in Table 7 were used to calculate the equivalence factor to Brent according to Equation 6.

Equation 10 – Price of refinery gas

$$P_{RG} = P_{NG} * \frac{HV_{RG}}{HV_{NG}}$$

Source: Prepared by the authors (2019)

Where:

P_{RG}	=	price of refinery gas	(USD/TOE)
P_{NG}	=	price of natural gas	(USD/TOE)
HV_{RG}	=	heating value of refinery gas	8,800 (kcal/kg) (EPE, 2014)
HV_{NG}	=	heating value of natural gas	10,454 (kcal/kg) (EPE, 2014)

Table 7 – Annual price of refinery gas in relation to the price of natural gas

Year	Price of natural gas	Price of refinery gas
	(USD/BOE)	
2004	199.85	168.23
2005	277.25	233.39
2006	365.92	308.02
2007	458.10	385.62
2008	508.06	427.68
2009	467.95	393.92
2010	522.14	439.53
2011	694.54	584.65
2012	711.43	598.87
2013	690.32	581.10

Source: Prepared by the authors (2019) based on EPE (2014), Table 8 e Equation 10.

2.6.2.5 Price of pellets

Wood pellets are biofuels made up of wood granules pressed from waste like sawdust or shavings. The price of pellets was taken from the AliceWeb database (BRAZIL, 2016), which provides this information from 2012. For standardization purposes, the conversion of primary data to USD/TOE unit was made using **Equation 11**.

Equation 11 – Price of wood pellet

$$F_p = \frac{P}{Q} * \frac{1}{H} * F$$

Source: Prepared by the authors (2019).

Where:

F_p	=	final price	(USD/TOE)
P	=	total price of pellet imports in the year excluding sea freight	(USD/FOB)
Q	=	total quantity of pellet imports in the year	(kg)
H	=	heating value of pellet	16.91 (MJ/kg) (1) (GARCIA; CARASCHI; VENTORIM, 2013)
F	=	MJ to TOE conversion factor	4.868×10^3 (MJ/TOE) (EPE, 2014)

(1) This is the measure of the low heating value (LHV) presented by the reference (GARCIA; CARASCHI; VENTORIM, 2013)

Equation 11 shows that the prices of pellets in 2012 and 2013 were USD 156.09/TOE and USD 146.67/TOE respectively. These prices were used to calculate the Brent-related equivalence factor according to **Equation 6**.

2.6.2.6 Price of refuse-derived fuel

RDF is the fuel resulting from the processing of waste that can be of municipal (MSW), industrial or agricultural origin. The price was based on a CDM Project Design Document Form (PDD) that proposed the partial replacement of fossil fuels with alternative fuels, including RDF, in a cement plant in Arabia (UNFCCC, 2012), since when this study was initiated no values for similar projects in Brazil were found. The price equivalent to 400 Egyptian pounds (EGP) was converted according to **Equation 12**.

Equation 12 – Price of refuse-derived fuel

$$F_p = \frac{P}{R} * \frac{F}{H}$$

Source: Prepared by the authors (2019)

Where:

F_p	=	final price	(USD/TOE)
P	=	RDF price used in the CDM Project	400 9 (EGP/t) (UNFCCC, 2012)
R	=	exchange rate for 2012	6.04 (EGP/USD) (UNFCCC, 2012)
H	=	heating value of RDF	14.349 (GJ/t) (UNFCCC, 2012)
F	=	GJ to TOE conversion factor	41.868 (GJ/TOE) (EPE, 2014)

After applying the formula, it was found that the RDF price in 2013 was USD 193.23/TOE. This price was used to calculate the Brent-related equivalence factor according to **Equation 6**.

2.6.2.7 Price of other fuels

The prices of other fuels were obtained from the BEN. The values for each year (in the period 2004 to 2013) are shown in **Table 8**.

Table 8 – Annual fuel price, 2004–2013

Fuel	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
	(USD/BOE)									
Fuel oil	38.5	52.1	61.5	66.3	78.1	69.4	81.5	87.9	77.7	74.4
Ethanol	115.8	158.4	214.9	243.9	258.5	231.4	262.6	334.7	277.8	262.5
Natural gas	28.4	39.4	52.0	65.1	72.2	66.5	74.2	98.7	101.1	98.1

Source: Adapted from EPE (2014).

2.6.2.8 Fuel equivalence factor

The equivalence factor was calculated annually using **Equation 6**. To calculate the average equivalence factor, a 10-year period was considered for each fuel. This period varied according to the data available in the time series. The average of the values found in this period for each fuel was calculated and then added to the MACTool, according to the "Average" column in **Table 9**.

Finally, the MACTool uses the average equivalence factors of each fuel obtained in **Table 9** and the Brent price according to Table 3 to project fuel prices up to 2030, according to **Equation 13**.

Equation 13 – Fuel price according to Brent

$$P_{fuel} = P_{Brent,x} * R_{fuel}$$

Source: Prepared by the authors (2019)

Where:

P_{fuel}	=	fuel price according to Brent	(USD/TOE) or (USD/BOE)
P_{Brent}	=	Brent price in year x	(USD/BOE)
R_{fuel}	=	fuel equivalence factor	(BOE/TOE) or (BOE/BOE)

These prices are found in the Time-Based Assumptions tab and are not used by the tool in any programmed calculations. However, they served as a database used by the consultants as a standardized reference in their analysis.

To facilitate data handling in the modeling, all prices were converted to US Dollar by Gigajoule unit (USD/GJ), as shown in **Table 10**.

2.6.3 Values associated with electricity fluxes in the MACTool

The MACTool has different approaches to the economic appreciation of electricity fluxes. For specific power generation or conservation projects, the calculation is based on the cost of the generation technology. In this case, the costs of a NG thermoelectric plant were used. This value was used when a technology generates power that is sold, for example, as cogeneration in the chemical industry. When the technology avoids power consumption, a portion corresponding to taxes was added to the cost of generation by the thermoelectric plant. This type of analysis was used, for example, for measures involving electric motors and lighting in the chemical industry.

Table 9 – Brent-related fuel equivalence factors

Fator de Equivalência	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	Average
	(BOE/BOE)	(BOE/TOE)									
Naphtha	n/a	1,17	1,08	1,39	0,96	1,08	1,13	1,04	1,01	1,03	**1,09**
NG	5,22	5,08	5,62	6,32	5,24	7,58	6,56	6,24	6,37	6,36	**6,06**
Firewood	1,85	1,94	2,07	2,12	1,84	2,81	2,48	1,94	1,69	1,59	**2,04**
FO	7,08	6,72	6,64	6,44	5,67	7,91	7,20	5,56	4,90	4,82	**6,30**
RG	4,40	4,28	4,73	5,32	4,41	6,38	5,52	5,25	5,36	5,35	**5,10**
Petroleum coke	0,57	0,62	0,74	0,95	1,10	1,02	1,47	1,50	1,02	1,00	**1,00**
Ethanol	21,30	20,43	23,21	23,69	18,76	26,37	23,21	21,17	17,51	17,02	**21,27**
Wood pellets	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	1,40	1,35	**1,37**
RDF	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	1,78	**1,78**

Source: Prepared by the authors (2019) based on Table 4 to Table 8 and MACTool calculation.
Note: n/a = data not available for the period.

Table 10 – Projection of fuel prices, 2014–2030

Fuel	2014	2015	2016	2017	2018	2019	2020	2021	2022
	(US$/GJ)								
Brent oil price	17.63	17.32	17.01	16.71	16.40	16.09	15.78	16.19	16.59
Naphtha	19.22	18.88	18.54	18.21	17.87	17.54	17.20	17.64	18.09
NG	15.61	15.34	15.07	14.80	14.52	14.25	13.98	14.34	14.70
Firewood	5.26	5.16	5.07	4.98	4.89	4.80	4.71	4.83	4.95
FO	16.23	15.95	15.67	15.38	15.10	14.81	14.53	14.90	15.28
RG	13.14	12.91	12.68	12.45	12.22	11.99	11.76	12.07	12.37
Petroleum coke	2.58	2.53	2.49	2.44	2.40	2.35	2.31	2.37	2.43
Ethanol	54.81	53.85	52.89	51.93	50.98	50.02	49.06	50.32	51.58
Wood pellets	3.53	3.47	3.41	3.34	3.28	3.22	3.16	3.24	3.32
RDF	192.03	188.67	185.32	181.96	178.61	175.25	171.89	176.32	180.74

Fuel	2023	2024	2025	2026	2027	2028	2029	2030	
	(US$/GJ)								
Brent oil price	17.00	17.33	17.81	18.14	18.46	18.79	19.12	19.44	
Naphtha	18.53	18.97	19.41	19.77	20.13	20.48	20.84	21.20	
NG	15.06	15.42	15.78	16.06	16.35	16.64	16.93	17.22	
Firewood	5.07	5.19	5.31	5.41	5.51	5.60	5.70	5.80	
FO	15.65	16.03	16.40	16.70	17.00	17.30	17.60	17.90	
RG	12.67	12.97	13.28	13.52	13.76	14.01	14.25	14.49	
Petroleum coke	2.48	2.54	2.60	2.65	2.70	2.75	2.79	2.84	
Ethanol	52.85	54.11	55.37	56.39	57.40	58.42	59.43	60.45	
Wood pellets	3.40	3.49	3.57	3.63	3.70	3.76	3.83	3.89	
RDF	185.16	189.58	194.00	197.56	201.12	204.68	208.24	211.80	

Source: Prepared by the authors (2019) based on the MACTool, Table 3 and Table 9.

The approach described above was used in the study to maintain consistency in relation to the use of the EF adopted in CDM projects, which in a way presupposes the expansion of the generation system by NG thermoelectric plants.

When it was necessary to determine spending on electricity, the purchase price of electricity by the final consumer (industry) was used. These values were used for both the BS and the LCS. The sale prices of electricity to distribution companies were used to determine the profits from adding power to the network through cogeneration projects, as was the case in the study.

The other approach used to determine electricity prices was through an exponential projection of electricity prices based on the values found in electricity auctions, provided by the Brazilian Electricity Regulatory Agency (ANEEL), plus a tax-related percentage. This approach is used for measures in which electricity consumption is included in energy costs, but in which the CO_2 mitigation technology is not related to electricity consumption (see **Table 2**).

2.6.3.1 Assumptions used to calculate the cost of generation by a thermoelectric plant

The values of electricity in this case were calculated using the MACTool, which calculates the revenue (electricity sales) according to the cost variables used: Actual Investment Flow per MWh, Levelized Investment per MWh, O&M per MWh, and Fossil Fuel cost per MWh.

2.6.3.1.1 *Actual investment flow per MWh*

The actual Capital Expenditure (CAPEX) per MWh was calculated based on the EIA (2015) "Electricity Market Module" document. For the composition of the investment cost, the value of USD 924/kW for a conventional combustion turbine was used, which is the value used in **Equation 14**.

Equation 14 – Investment cost per megawatt hour

$$CAPEX_{MWh} = \frac{CAPEX * 1{,}000}{8{,}760 * FC}$$

Source: Prepared by the authors (2019)

Where:

$CAPEX_{MWh}$	=	investment per MWh	(USD/MWh)
CAPEX	=	investment	924(USD/kw) (EIA, 2015, p. 97)
1000	=	kW to MW conversion	(kW/MW)
8,760	=	hours in a year	(h/year)
CF	=	capacity factor	42 (%) (SCHLÖMER, 2014)

After applying Equation 14, an investment of USD 250/MWh was obtained for 2014. This value was not used by the MACTool in the calculation of electricity prices. However, it was used to obtain the levelized value, as described in **Equation 15**.

2.6.3.1.2 *Levelized investment per MWh*

The levelized investment per MWh was calculated from USD 924/kW using **Equation 15**.

The result of Equation 15 was the levelized investment corresponding to USD 22.18/MWh. This amount was included for all years from 2014 to 2030.

Equation 15 – Levelized investment cost per megawatt hour

$$CAPEX_{lvl} = \frac{CAPEX * CRF * 1{,}000}{E}$$

Source: Prepared by the authors (2019)

Where:

$CAPEX_{lvl}$	=	levelized investment	(USD/MWh)
CAPEX	=	investment	924 (USD/kW) (EIA, 2015, p. 97)
CRF	=	Capital Recovery Factor (1)	8.88 (%)
1,000	=	kW to MW conversion	(kW/MW)
E	=	energy generated in a year by the turbine	3,700 (kWh)

(1) Calculated by Microsoft Excel using the PGTO function with the discount rate values (8% p.a.) and the turbine life cycle (30 years according to Schlömer, 2014, p.1333) and the value of –1 for the investment.

2.6.3.1.3 *Operation and maintenance per MWh*

Operation and maintenance costs per MWh were calculated from the values provided by the EIA (2015), using **Equation 16**.

Equation 16 – Operation and maintenance cost per megawatt hour

$$O\&M_{MWh} = O\&M_{var} + \left(\frac{O\&M_{fix} * 1{,}000 * CF}{8{,}760}\right)$$

Source: Prepared by the authors (2019)

Where:

$O\&M_{MWh}$	=	total operation and maintenance cost per MWh	(USD/MWh)
$O\&M_{var.}$	=	variable operation and maintenance cost	15.45 (USD/MWh) (EIA, 2015, p. 97)
$O\&M_{fix}$	=	fixed operation and maintenance cost	7.34 (USD/kW) (EIA, 2015, p. 97)
1,000	=	kW to MW conversion	(kW/MW)
CF	=	capacity factor	42 (%) (SCHLÖMER, 2014)
8,760	=	hours in a year	(h/year)

The operational expenditure (OPEX) of USD 15.80/MWh — which was used in all years from 2014 to 2030 — was obtained from **Equation 16**.

2.6.3.1.4 *Fossil fuel cost per MWh*

The fuel cost per MWh was calculated based on the NG prices, according to **Equation 17**. NG prices were calculated from the Brent oil price and the equivalence factor, as described in section 2.6.2.

Equation 17 – Calculation of fuel costs per megawatt hour

$$EC_{MWh} = \frac{P_{year}}{F * E}$$

Source: Prepared by the authors (2019).

Where:

EC_{MWh}	=	energy cost per MWh	(USD/MWh)
P_{year}	=	price of natural gas in the year in question	(USD/TOE)
F	=	TOE to MWh conversion factor	11,63 (MWh/TOE) (adapted from EPE, 2014)
E	=	turbine efficiency(1)	34 (%)

(1) Efficiency was calculated from the EF of natural gas, 0.2 tCO_2/MWh (based on CETESB, 2010) and the EF of electricity using the CDM methodology, 0.5884tCO_2/MWh (based on BRAZIL, [2015?])

Finally, the values resulting from Equations 15 to 17, which were entered year by year in the MACTool, are shown in **Table 11**.

Table 11 – Costs associated with electricity production (Power Baseline)

Year	Levelized investment	Operation and maintenance	Power cost
	(USD/MWh)		
2014	22.18	15.80	165.38
2015	22.18	15.80	162.49
2016	22.18	15.80	159.60
2017	22.18	15.80	156.72
2018	22.18	15.80	153.83
2019	22.18	15.80	150.94
2020	22.18	15.80	148.05
2021	22.18	15.80	151.85
2022	22.18	15.80	155.66
2023	22.18	15.80	159.47
2024	22.18	15.80	163.28
2025	22.18	15.80	167.09
2026	22.18	15.80	170.15
2027	22.18	15.80	173.22
2028	22.18	15.80	176.28
2029	22.18	15.80	179.35
2030	22.18	15.80	182.42

Source: Prepared by the authors (2016) based on Equation 14 to Equation 17.
Note: Data are estimates.

2.6.3.2 Electricity prices based on electricity auctions (generation price)

In this approach, electricity generation prices are based on the results of the most recent electricity auctions made available by ANEEL ([2015?]). Based on auction prices, annual weighted averages were produced considering the power of the plants (MW) and the price per energy source (R$/MWh) at which the energy was sold. The weighting was applied so that the average price could better represent the value of large energy producers, mainly hydroelectric and thermoelectric plants.

The selected period was from 2013 to 2020[13]. Next, for projecting prices up to 2030, an exponential model was used, calculated according to **Equation 18** and based on the values of the latest auctions.

Equation 18 – Exponential regression of electric energy auction prices 2013–2020 ($r^2 = 0.51$)

$$P_y = 32.301\ e^{0.0983\ (a\ -\ 2003)}$$

Source: Prepared by the authors (2019) from ANEEL (2015)

Where:

P_y	=	price of electricity in the year in question	(R$/MWh)
y	=	year in question	(dimensionless)

13. For the period 2016–2020, the auctions of projects for plants that will operate in the future were used, such as 2020 auctions, which refer to projects auctioned in 2015 that will be operational in five years. That is why they are called "2015 A-5".

Chart 5 presents the exponential projection and data of energy auctions carried out in 2013–2020 (ANEEL, [2015?]).

2.6.4 Electricity prices for end consumers

Electricity prices for end consumers were projected from generation prices, plus a tax-related percentage and the transmission rate in both the auction prices and the prices of a thermoelectric plant. In the case of prices based on a thermoelectric plant, this percentage was introduced directly in the MACTool, in each technology related to electricity conservation or generation. In the case of auction prices, this percentage was added outside the tool, in the amount that makes up the energy costs of other technologies that are not related to electricity conservation or generation.

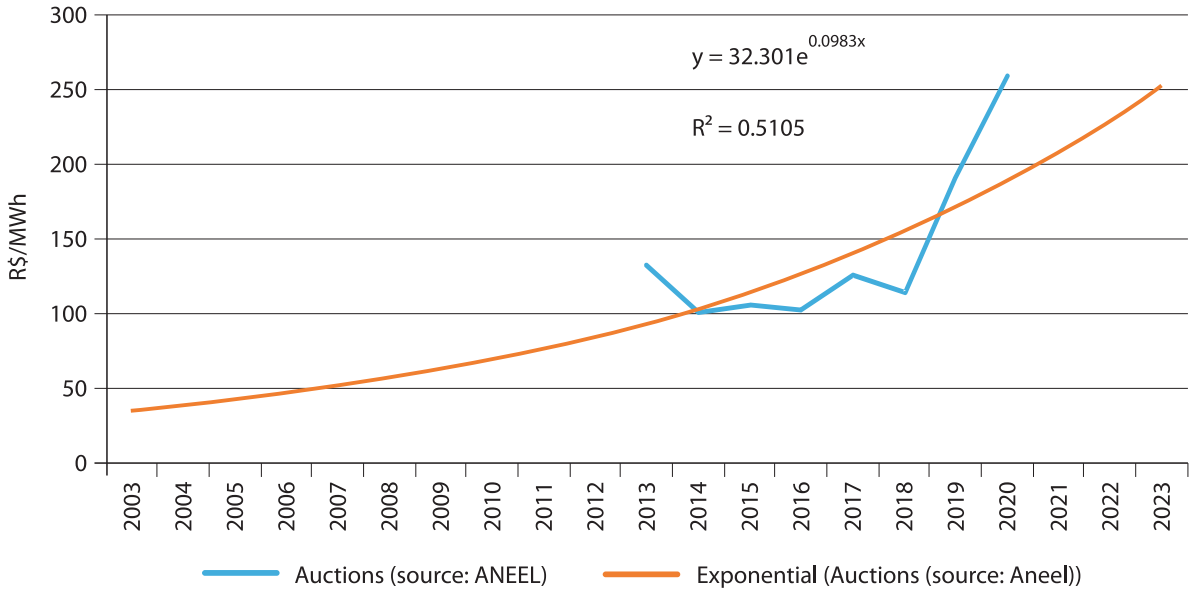
The calculation of this percentage was based on data provided by ANEEL's Tariff Management Superintendence (Superintendência de Gestão Tarifária – SGT), where monthly data for electricity concessionaires in the State of Sao Paulo were presented. These data are shown in Box 3.

Box 3 – Electricity concessionaires in the State of Sao Paulo

Electricity concessionaires (SP)
CNEE – Companhia Nacional de Energia Elétrica
CPFL Leste Paulista – Companhia Leste Paulista de Energia
CPFL- Piratininga – Companhia Piratininga de Força e Luz
EDEVP – Empresa de Distribuição de Energia Vale Paranapanema S/A
Elektro – Elektro Eletricidade e Serviços S/A.
Caiuá-D – Caiuá Distribuição de Energia S/A
CPFL Jaguari – Companhia Jaguari de Energia
CPFL Sul Paulista – Companhia Sul Paulista de Energia
CPFL-Paulista – Companhia Paulista de Força e Luz
EEB – Empresa Elétrica Bragantina S/A.
Eletropaulo – Eletropaulo Metropolitana Eletricidade de São Paulo S/A

Source: Prepared by the authors (2019) based on data provided by SGT ANEEL.

Chart 5 – Exponential projection for energy auction prices



Source: Prepared by the authors (2019) based on ANEEL ([2015?])
Note: Data refer to 2013 to 2020. All other figures are projections.

Equation 19 — which establishes the calculation of the percentage of taxes on the cost of electricity generation — was applied using reference data classified as "industrial" for each concessionaire.

Equation 19 – Calculation of the monthly percentage of electricity taxes

$$E_t = \frac{R_E - R_D}{R_E - R_D - Pis\_Pasep\_Cofins - ICMS} - 1$$

Source: Prepared by the authors (2019)

Where:

E_t	=	percentage of electricity tax	(%)
R_E	=	total revenue collected by the concessionaire	(R$)
R_D	=	charge added when a given industry exceeds the established demand	(R$)
PIS PASEP COFINS and ICMS	=	government taxes	(R$)

Equation 19 was used to obtain the monthly values for each concessionaire and then the average value for all concessionaires was calculated for 2013, which is the base year of this study. The average result of 24% indicates the tax amount that is added to the price of electricity generation. The final electricity purchase and sale prices are shown in **Table 12**, which also compares the prices of the auctions approach with the previous approach, i.e. the NG plant.

2.7 ELECTRICITY – NETWORK LOSSES

Electricity losses from transmission are represented by an average value that is an important MACTool assumption for all calculations involving CO_2 emission from variation in electricity consumption. Due to these energy losses, avoided CO_2 emissions per kilowatt-hour (kWh) consumed are in fact higher than the average emissions from generators, since according to **Equation 20**, the actual emission is given by

Table 12 – Projection of electricity purchase and sale prices

Year	NG plant		Electricity auctions	
	Generation price	Price for end consumers	Generation price	Price for end consumers
	(USD/MWh)			
2014	203.37	252.32	44.09	54.70
2015	200.48	248.73	48.65	60.35
2016	197.59	245.15	53.67	66.59
2017	194.70	241.56	59.22	73.47
2018	191.81	237.98	65.33	81.06
2019	188.92	234.39	72.08	89.43
2020	186.03	230.81	79.53	98.67
2021	189.84	235.53	87.74	108.86
2022	193.65	240.25	96.80	120.10
2023	197.46	244.98	106.80	132.51
2024	201.26	249.70	117.84	146.20
2025	205.07	254.43	130.01	161.30
2026	208.14	258.23	143.44	177.96
2027	211.21	262.04	158.25	196.34
2028	214.27	265.84	174.60	216.62
2029	217.34	269.64	192.63	238.99
2030	220.40	273.45	212.53	263.68

Source: Prepared by the authors (2019).
Note: Data are estimates.

the emission from consumption plus the percentage lost in the network or in any other way.

Data on electricity losses for the Southeast and Central-West regions were taken from the Ten-Year Energy Expansion Plan (PDE) 2023 (BRAZIL, 2014). Only values for the years 2014, 2018 and 2023 are shown. Therefore, the linear interpolation of the loss values for intermediate

Equation 20 – Actual electricity generated by electricity losses in the network

$$Electricity\ generated = Electricity\ consumed * (1 + losses)$$

Source: Prepared by the authors (2019)

Where:

Electricity generated	=	electricity amount generated including losses	(kWh)
Electricity consumed	=	electricity amount consumed	(kWh)
Losses	=	electricity percentage lost in the network	(%)

years was performed, using the same formula described in **Equation 5**. The interpolated values are shown in **Chart 6**, along with the values taken from the PDE 2023 in bold font. They were added to the MACTool.

In this study, losses in the network were considered in the measures related to electricity. The measures were: (i) NG cogeneration; (ii) Lighting using light emitting diode (LED) lamps; (iii) Electric motors; (iv) Preheating and continuous feed furnaces; (v) Direct current furnaces; (vi) Maerz kiln using biomass in natura; and (vii) Maerz kiln using torrefied biomass.

2.8 DISCOUNT RATE

The discount rate used in the project to calculate the MAC is 8% per year (p.a.). This is the same value used in the World Bank study, which also used the MACTool (GOUVELLO et al., 2010), since it is what generally corresponds to the cost of loans used by the Brazilian Bank for Economic and Social Development (BNDES) to finance projects.

Also called "social discount rate", this rate is the same for all low-carbon measures, which differs in the case of the BECP, in which the IRR Benchmark is applied to each measure.

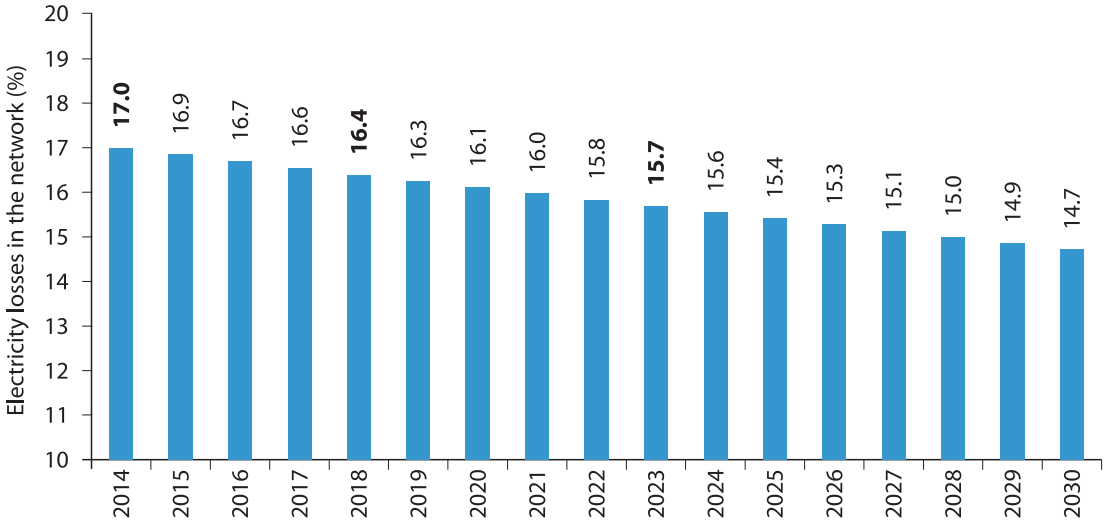
2.9 LONG-TERM INTEREST RATE (LTIR)

The Long-Term Interest Rate (LTIR), which was established by Provisional Decree No. 684 of 10/31/1994 and published in the Federal Official Gazette in 03/1994, is defined as the basic cost of financing granted by the BNDES. It was amended by Provisional Decree No. 1,790 of 12/22/98 and Provisional Decree No. 1,921 of 09/30/1999, later converted into Law 10,183 of 02/12/2001 (BNDES, 2016).

The LTIR provided by the BNDES (2011) is valid for one quarter, expressed in annual terms and calculated based on the following parameters:

- [illegible]

Chart 6 – Electricity losses for the Southeast region, 2013–2030



Source: Prepared by the authors (2019) based on Ministry of Mines and Energy (BRAZIL, 2014).
Note: Figures for 2014, 2018 and 2023 are data. All other figures are projections.

■ [illegible]

According to the BNDES (2011), the LTIR is applied to:

i) BNDES passive contracts with the Workers' Assistance Fund (FAT); PIS-PASEP Participation Fund; and Merchant Marine Fund (FMM);

ii) BNDES active contracts with funds from the same funds as in item i);

iii) Remuneration of the accounts of participants in the PIS-PASEP Participation Fund;

iv) Other cases, at the discretion of the National Monetary Fund (CMN).

However, according to the calculation methodology in relation to BNDES contracts linked to the LTIR, there is also a basic spread (which varies according to BNDES System Operational Policies) and a risk spread (which varies according to the client's risk rating).

Considering the annual averages of the LTIR value for the period 2006 to 2016, with the latter up to the first semester, an average value of 6.19% was obtained (BNDES, 2016) and considering the possible incidence of both the basic spread and the risk spread, a rate of 8% p.a. was estimated for use in the study

2.10 ATTRACTENESS RATE (IRR BENCHMARK)

The attractiveness rate (IRR Benchmark) used to calculate the BECP varies according to the targets of each investor, based on risks associated with project implementation and market conditions. Therefore, an IRR Benchmark was

Table 13 – IRR benchmark by industrial sector

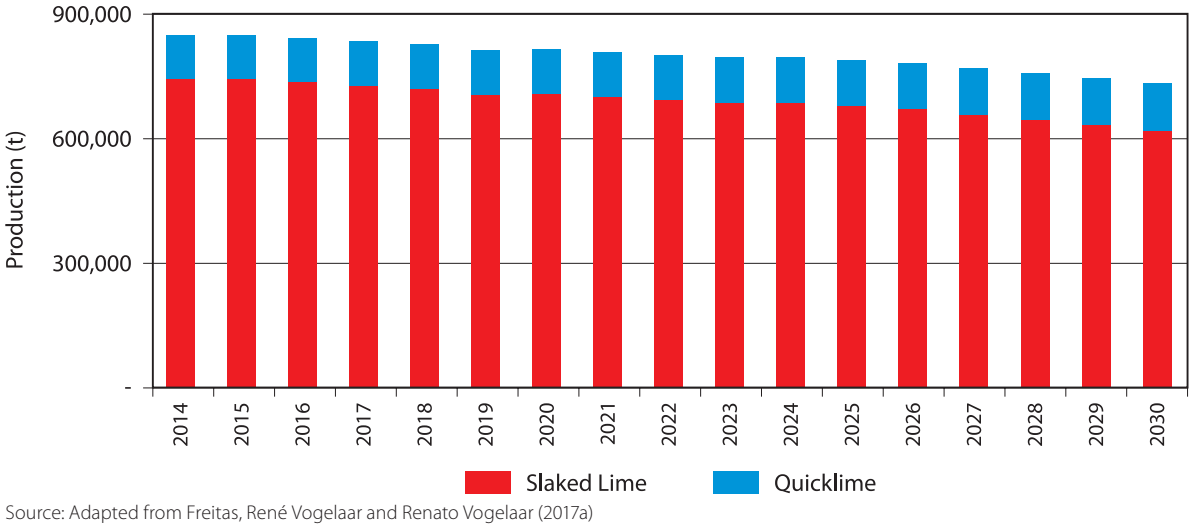
Industry	IRR benchmark (%)
Lime	15
Steel	15
Chemical	18
Cement	13
Construction (1)	22

Source: Prepared by the authors (2019) based on Freitas, René Vogelaar and Renato Vogelaar (2017a; 2017b), Punhagui et al. (2017), Fanti et al. (2017).
(1) Used to calculate the BECP shown in Appendix A.

identified for each industrial sector based on the specialists' consultations with the sectors. These rates are shown in **Table 13**.

2 Scenarios and specific analysis by industrial sector

Chart 7 – Production scenario for quicklime and slaked lime



Source: Adapted from Freitas, René Vogelaar and Renato Vogelaar (2017a)
Note: Figures for 2013 are data; all other figures are projections.

3.1 LIME INDUSTRY

This section presents the summary of the study developed for the lime industry in the State of Sao Paulo.

3.1.1 Baseline scenarios

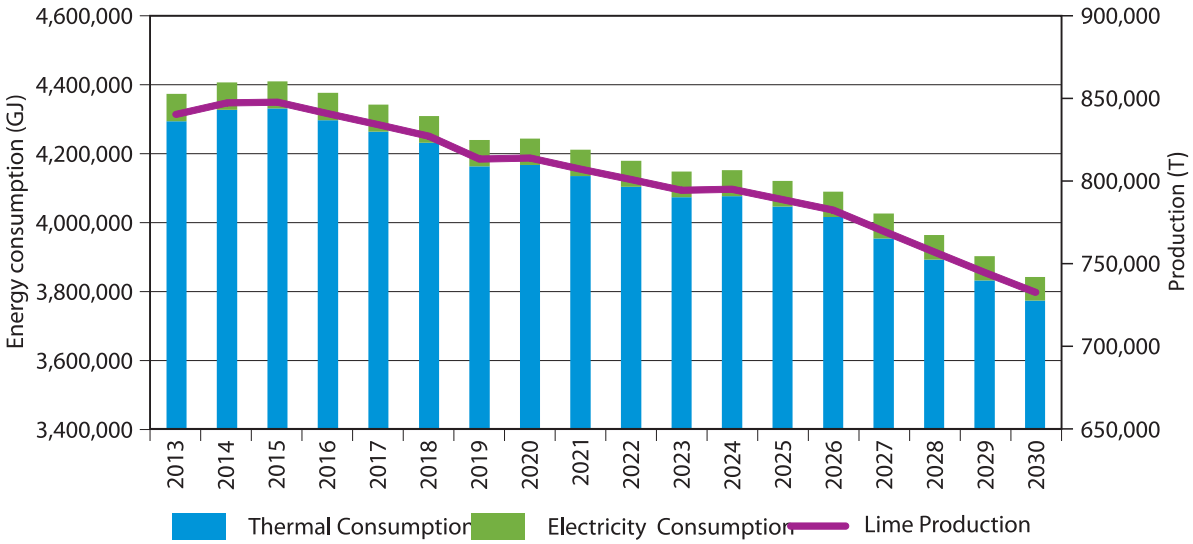
This sub-item presents the BS for the physical production of lime (quicklime and slaked lime), thermal energy and electricity consumption, and GHG emissions from process and energy.

Table 14 – Projection of thermal energy and electricity consumption for the lime industry, 2013 to 2030

Year	Production	Thermal energy consumption	Electricity consumption
	(t)	(GJ)	(MWh)
2013	840,000	4,292,171	21,870
2014	846,850	4,325,359	22,039
2015	847,355	4,328,530	22,056
2016	840,442	4,295,043	21,885
2017	833,607	4,261,954	21,716
2018	826,852	4,229,261	21,550
2019	812,971	4,161,359	21,204
2020	813,502	4,164,692	21,221
2021	806,979	4,133,170	21,060
2022	800,532	4,102,030	20,901
2023	794,161	4,071,270	20,745
2024	794,713	4,074,738	20,762
2025	788,422	4,044,389	20,608
2026	782,204	4,014,413	20,455
2027	769,347	3,951,629	20,135
2028	756,765	3,890,207	19,822
2029	744,451	3,830,122	19,516
2030	732,401	3,771,348	19,216

Source: Prepared by the authors (2019) based on Freitas, René Vogelaar and Renato Vogelaar (2017a)
Note: Data are estimates.

Chart 8 – Projected thermal energy and electricity consumption in the lime industry



Source: Prepared by the authors (2019) based on Freitas, René Vogelaar and Renato Vogelaar (2017a).
Note: Data: 2013. All other figures are estimates.

3.1.1.1 Lime production in the baseline scenario

Data for the projection were taken from the time series (1990–2013) of the Brazilian Association of Lime Producers (ABPC). The assumptions for projecting lime production up to 2030 were: (a) for quicklime lime (industrial lime), current production amounts will stand; new amounts of industrial lime that may be needed will be purchased in the market, as this is an industry that depends on scale, and a new industrial scale unit in the state would not have mineral reserves of the necessary quality; and (b) in relation to slaked lime (lime for construction), the tendency is for mortar prepared on site to be replaced by industrialized mortar (ready-to-use mortar). In addition, another factor, which also contributes to reducing the amount of slaked lime, is the tendency to replace it with chemical products called air incorporators (FREITAS; VOGELAAR, René; VOGELAAR, Renato, 2017a). The lime production scenario is shown in **Chart 7**. According to this scenario, an average annual reduction of 0.8% will occur in the period 2013 to 2030.

Table 15 – Lime composition and emission factors

	Emission factor ($tCO_2/tcal$)	Quicklime	Slaked lime
Calcitic	0.800	100%	16%
Dolomitic	0.903	0%	24%
Magnesian	0.854	0%	39%
Water	—	0%	21.3%
Average emission factor (tCO_2/t_{lime})		0.800	0.675

Source: Prepared by the authors (2019) based on MCT (BRAZIL, 2010).

3.1.1.2 Energy consumption in the baseline scenario

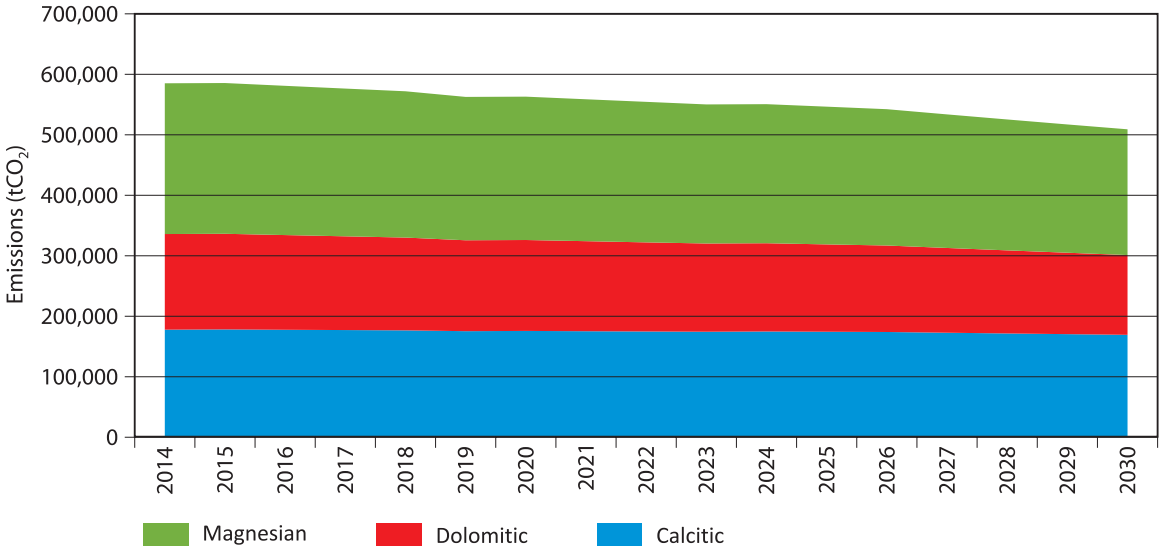
Fuel consumption for lime furnaces and electricity consumption in the BS are shown in **Table 14**. This estimate considers that thermal energy and electricity consumption per ton of lime

Table 16 – Projected CO_2 emissions by type of lime, 2014 to 2030

Year	Chemical type				Commercial type		
	Calcitic	Dolomitic	Magnesium	Total	Quicklime	Slaked lime	Total
	(tCO_2)						
2014	177,077	158,268	249,466	**584,810**	83,600	501,210	**584,810**
2015	177,481	158,268	249,466	**585,214**	84,004	501,210	**585,214**
2016	176,954	156,685	246,971	**580,610**	84,412	496,198	**580,610**
2017	176,441	155,118	244,502	**576,061**	84,824	491,236	**576,061**
2018	175,941	153,567	242,057	**571,564**	85,240	486,324	**571,564**
2019	174,547	150,496	237,215	**562,258**	85,661	476,598	**562,258**
2020	174,972	150,496	237,215	**562,683**	86,085	476,598	**562,683**
2021	174,512	148,991	234,843	**558,346**	86,514	471,832	**558,346**
2022	174,065	147,501	232,495	**554,061**	86,947	467,113	**554,061**
2023	173,631	146,026	230,170	**549,827**	87,385	462,442	**549,827**
2024	174,073	146,026	230,170	**550,269**	87,827	462,442	**550,269**
2025	173,657	144,566	227,868	**546,091**	88,273	457,818	**546,091**
2026	173,254	143,120	225,590	**541,963**	88,724	453,239	**541,963**
2027	172,018	140,258	221,078	**533,354**	89,179	444,175	**533,354**
2028	170,821	137,452	216,656	**524,930**	89,639	435,291	**524,930**
2029	169,662	134,703	212,323	**516,689**	90,103	426,585	**516,689**
2030	168,540	132,009	208,077	**508,626**	90,572	418,054	**508,626**

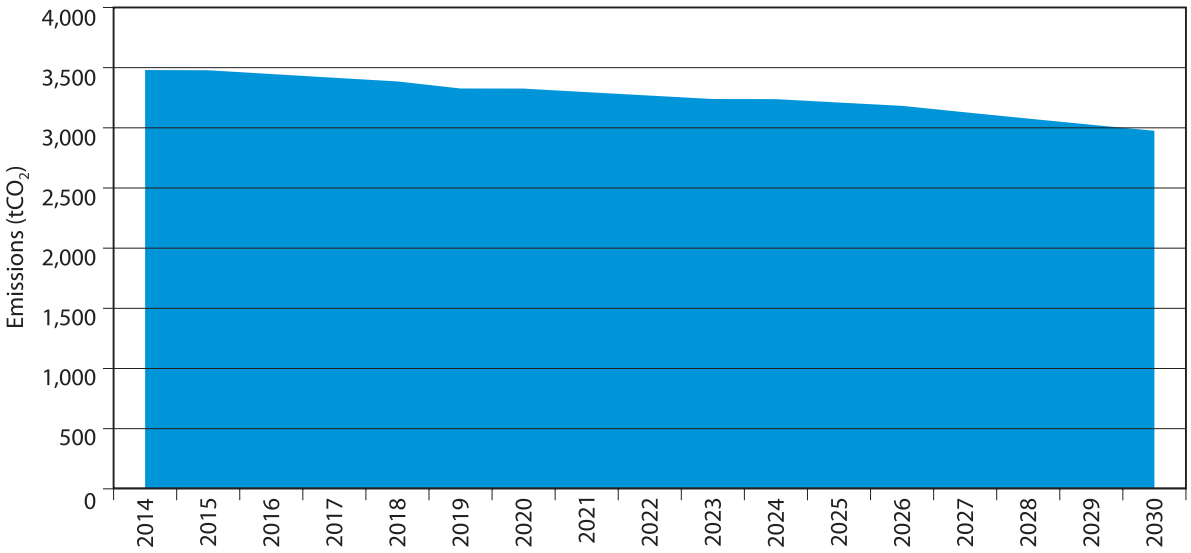
Source: Adapted from Freitas, René Vogelaar and Renato Vogelaar (2017a).

Chart 9 – Scenario of CO_2 emissions from the calcination process



Source: Adapted from Freitas, René Vogelaar and Renato Vogelaar (2017a).

Chart 10 – Scenario of CO_2 emissions from energy consumption



Source: Adapted from Freitas, René Vogelaar and Renato Vogelaar (2017a).

are 6.28 GJ and 0.12 GJ (32 kWh) respectively, excluding the portion corresponding to water in slaked lime.

Chart 8 was prepared using data from **Table 14**. It is observed that there is a tendency towards reducing energy consumption and lime production in the period. This reduction is due

to the decrease in lime production in the state (**Chart 7**).

3.1.1.3 CO_2 emissions in the baseline scenario

For the projection of CO_2 emissions from industrial processes, the EF used for each type of lime were taken from CETESB's inventory (2011) and BRAZIL (2010). Quicklime is composed exclusively of calcitic lime, while slaked lime is composed of calcitic lime, dolomitic lime, magnesian lime and a percentage of water, which was disregarded in the calculation of emissions, as shown in **Table 15**.

Table 16 shows the projection of emissions for the State of Sao Paulo by type of lime and chemical composition (calcitic, dolomitic and magnesian) and by commercial type in the period 2014 to 2030.

Chart 9 shows emissions from 2014 to 2030, using data and lime production in 2013 (ABPC, 2014) and production data estimated from that same year, according to the values presented in **Table 16**.

Considering that renewable firewood and electricity are used in lime processing (FREITAS; VOGELAAR, René; VOGELAAR, Renato, 2017a), only the EF from electricity was used to calculate emissions, since wood from planted forests has zero emission, as discussed in Section 2.3.3 of this report. Emissions from energy consumption are shown in **Chart 10**.

Chart 9 and **Chart 10** show a decreasing trend in CO_2 emissions, since emissions from both process and energy are directly related to the physical production of lime, which is decreasing in the period. That is, in the BS there is already a dematerialization, or a reduction in lime consumption in the state that leads to the overall reduction of emissions from this sector.

3.1.2 Low carbon scenario

The scenario presented shows that emissions are decreasing due to the retraction of the lime market in the state. The substitution of lime in the construction industry for other technologies and the increased efficiency in its use are two reasons that explain the reduction in the use of lime, without a reduction in the consumption of lime-based products. That is, the lime industry is already showing an intrinsic reduction in emissions due to market trend.

The introduction of low-carbon technologies could further reduce emissions by 2030. However, the search for measures that accelerate the replacement of lime with other substances (e.g. air incorporators and mortar) could also be considered as low carbon options. In addition, the shutdown of USIMINAS' high furnace is expected to affect the already limited state production of quicklime, as the demand for this product will decrease. The technologies, barriers, and emissions in the LCS for the lime industry considered in the study are presented below.

3.1.2.1 CO_2 mitigation technologies in the low carbon scenario

For the lime sector it is possible to consider technologies that reduce emissions from industrial processes and technologies that reduce emissions from energy consumption.

To reduce emissions from processes — which represent approximately 99.4% of CO_2 emissions in the BS — the CCS process was considered (FREITAS; VOGELAAR, René; VOGELAAR, Renato, 2017a). To reduce energy emissions, the following technological alternatives were evaluated, which entail replacing the Azbe kiln with the Maerz kiln fed by (a) biomass in natura and (b) torrefied biomass. From a total of 5 kilns to be replaced in the LCS, 4 will use biomass in natura and 1 will use torrefied

biomass (FREITAS; VOGELAAR, René; VOGELAAR, Renato, 2017a).

It is important to clarify that in the BS renewable biomass is already the fuel used in Azbe kilns (for the State of Sao Paulo). Therefore, there is no reduction of CO_2 emissions in the LCS, because in both cases the EF is null. However, it is assumed that when the Maerz kiln is used, either with biomass in natura or torrefied biomass, there will be an energy efficiency that would provide biomass for other purposes and industries. Therefore, the reduction of CO_2 emissions in the LCS implies an increase in the supply of renewable energy that could be shifted to another industry, replacing the fossil fuel with biomass. This can be seen in the wedges in **Chart 13**. For the purposes of this estimate, the fossil fuel to be replaced was petroleum coke. The EF of the coke shown in Table 1 was used to determine the emission avoided by the energy savings from the comparison between the BS and the LCS. With the use of firewood in a more efficient kiln, an additional amount of it is available on the market for use in other applications that would normally use petroleum coke, which is a low-carbon option.

3.1.2.1.1 *Carbon Capture and Storage*

CCS was used as a technology to reduce emissions from the lime production process. This technology involves capturing, transporting, injecting and depositing CO_2 in geological structures. Large-scale commercial CCS systems are still being developed, but there are already several pilot projects demonstrating this technology. CCS allows saving time in the transition to low carbon-emitting technologies. In fact, a technique like Enhanced Oil Recovery (EOR) enables using gas as a fluid for injecting and recovering oil or NG in wells nearing exhaustion (APEC, 2012).

Other benefits involved in the use of CCS include: reduction of CO_2 in the atmosphere; development of a sustainable economy with possible job creation; possible secondary revenue flow with carbon converted into a tradable commodity (APEC, 2012). The implementation cost as well as the operation and maintenance cost of a CCS system per ton of avoided CO_2 emissions were assessed by the authors at USD28,80 and USD71,35/tCO_2 respectively (FREITAS; VOGELAAR, René; VOGELAAR, Renato, 2017a).

3.1.2.1.2 *Maerz Kiln using biomass in natura*

The most common kilns used by the lime industry in Brazil are Azbe, Maerz, rotary and masonry kilns (FREITAS; VOGELLAR, René; VOGELAAR, Renato, 2017a). In Sao Paulo's industrial sectors, Azbe kilns fueled by carbonated wood are the predominantly used technology. The Maerz kiln, which is the regenerative parallel-flow vertical shaft kiln, is the most energy efficient. Although the Azbe kiln is more efficient than simple masonry kilns, replacing an Azbe kiln with a Maerz kiln enables achieving a 39% reduction in thermal energy consumption. Maerz kilns can use various types of fuel, including renewable biomass.

While a traditional Azbe kiln has an implementation cost of USD16 million, a Maerz kiln costs USD24.3 million. The operating cost of an Azbe kiln and that of a Maerz kiln have an average between quicklime and slaked lime of USD36/$t_{product}$ and USD40/$t_{product}$ respectively.

3.1.2.1.3 *Maerz Kiln using torrefied biomass*

Torrefaction is a pretreatment aimed to increase the carbon content in biomass, thereby

increasing the amount of energy per mass unit. The advantages of torrefied biomass compared to biomass in natura are: higher heating value, greater milling capacity, hydrophobicity (water contributes to the biological degradation of wood), ease of transportation and handling, and low explosivity due to the elimination of volatiles (DUTTA and LEON, [2015?]). For torrefaction, the Poltorr system patented by Thyssen Krupp can contribute to reducing CO_2 emissions. It is an autogenous furnace that controls temperature by exchanging gas between the two chambers of the unit (drying and torrefaction), and that can use not only cultivated biomass but also, for example, municipal solid waste. The use of this technology suggests attention to the possible emission of other pollutants.

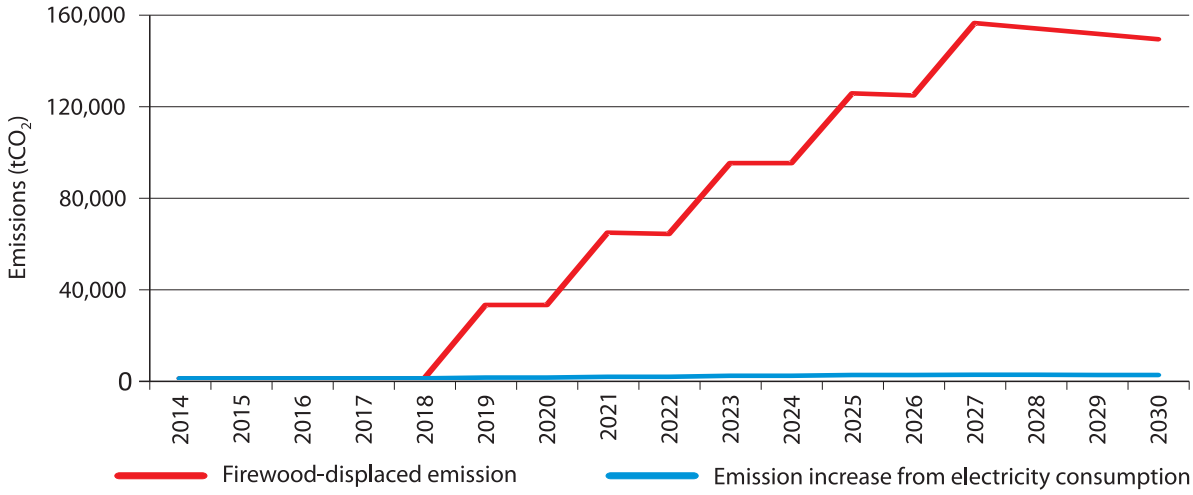
The cost of implementing a Maerz kiln using torrefied biomass is USD27.3 million, about USD3 million more than with biomass in natura, and its operation and maintenance cost is USD41/t_{lime} (average between quicklime and slaked lime).

Table 17 – Comparison between the baseline and low carbon scenarios in the lime industry: energy consumption and respective emission

Year	Electricity consumption			Thermal energy consumption		
	BS	LCS	Increase in electricity emission in the LCS	BS	LCS	Emission avoided by energy savings and shifting petroleum coke
	(MWh)		(tCO_2)	(GJ)		(tCO_2)
2014	22,039	22,039	0	4,325,359	4,325,359	0
2015	22,056	22,056	0	4,328,530	4,328,530	0
2016	21,885	21,885	0	4,295,043	4,295,043	0
2017	21,716	21,716	0	4,261,954	4,261,954	0
2018	21,550	23,974	0	4,229,261	4,229,261	0
2019	21,204	23,589	376	4,161,359	3,839,547	32,125
2020	21,221	25,995	376	4,164,692	3,842,623	32,151
2021	21,060	25,799	745	4,133,170	3,493,906	63,814
2022	20,901	27,956	738	4,102,030	3,467,583	63,334
2023	20,745	27,746	1,098	4,071,270	3,126,735	94,288
2024	20,762	30,105	1,097	4,074,738	3,129,399	94,368
2025	20,608	29,881	1,450	4,044,389	2,793,325	124,887
2026	20,455	30,682	1,438	4,014,413	2,772,621	123,962
2027	20,135	30,203	1,571	3,951,629	2,392,053	155,685
2028	19,822	29,733	1,544	3,890,207	2,354,872	153,265
2029	19,516	29,274	1,519	3,830,122	2,318,501	150,898
2030	19,216	28,825	1,494	3,771,348	2,282,923	148,582

Source: Prepared by the authors (2019) based on Freitas, René Vogelaar and Renato Vogelaar (2017a).

Chart 11 – Lime industry: energy emissions in the low carbon scenario, comparison between emissions from thermal energy and electricity



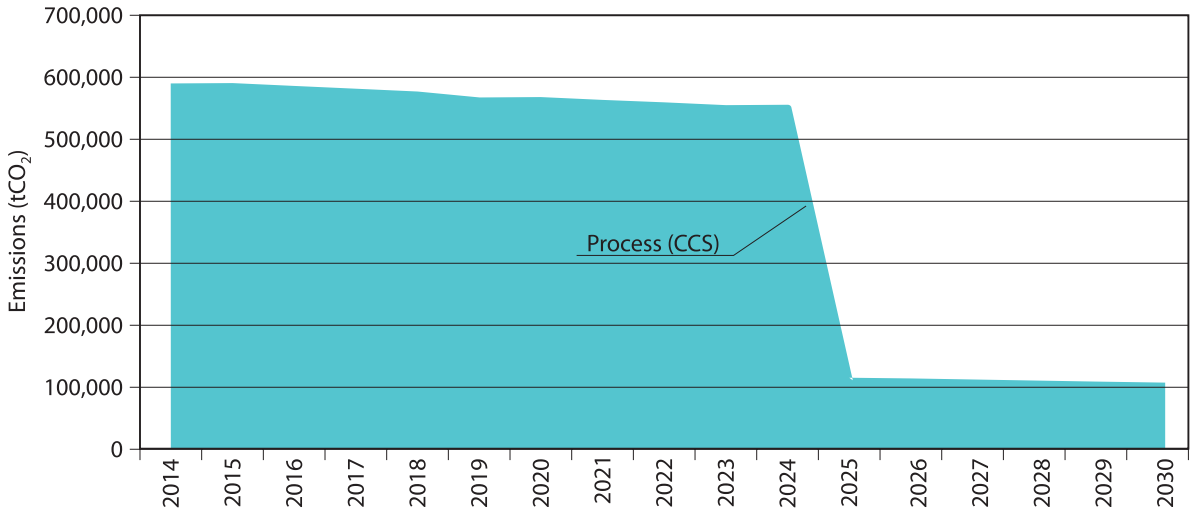
Source: Prepared by the authors (2019) based on Table 17.

3.1.2.2 Barriers to the development of the low carbon scenarios proposed

Maerz kilns use more electricity than Azbe kilns. Reduction, therefore, occurs by offsetting the decrease in thermal energy consumption. However, it should be noted that changes in the Brazilian electrical matrix may cause significant variations in the emission balance of these technologies. Another point is that due to investment costs, the kilns will not be attractive from the economic standpoint, unless there is governmental incentive (FREITAS; VOGELAAR, René; VOGELAAR, Renato, 2017a).

In turn, CCS is still a high-cost technology with few national references, whose implementation is not foreseen within the project

Chart 12 – Lime industry: emissions from lime process in the low carbon scenario



Source: Prepared by the authors (2019) based on Freitas, René Vogelaar and Renato Vogelaar (2017a).

horizon. However, a modeling including CCS in the last years of the period of analysis was attempted. Because it is still in the experimental stage, there were considerable difficulties in assessing CCS implementation and operation costs. Most of the cases found were large-scale

Table 18 – Lime industry: Marginal Abatement Cost and Break-Even Carbon Price

Type of MACTool approach	Measure/ technology	MAC	BECP	Avoided emissions 2014–2030
		(USD/tCO_2)		($MtCO_2$)
Fossil	Maerz kiln using torrefied biomass	12	93	0.13
Fossil	Maerz kiln using biomass *in natura*	17	94	1.09
Process	CCS	29	98	2.54

Source: Prepared by the authors (2019) based on Freitas, René Vogelaar and Renato Vogelaar (2017a).

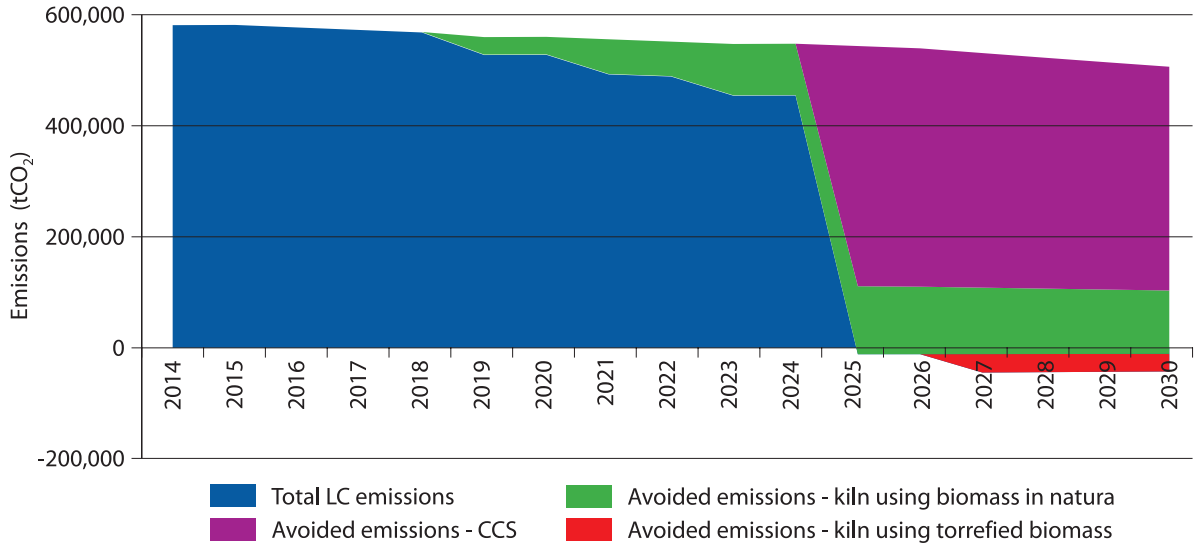
emission projects such as thermoelectric plants, and it is not feasible to extrapolate the costs to small-scale emission cases, as is the case of lime factories. To consider the implementation of a CCS system in the lime sector, all carbon transportation and storage costs were also disregarded, since this infrastructure should not be the responsibility of the industry alone (FREITAS; VOGELAAR, VOGELAAR, Renato, 2017a).

3.1.2.3 CO_2 emissions in the low carbon scenario

The main characteristic of the LCS is the fact that Maerz kilns use more electricity than Azbe kilns, thus increasing emissions from electricity in the LCS. However, this increase is negligible compared to the emission that would be avoided considering the savings in thermal energy and shifting of firewood to other sectors that use fossil fuel, such as the emission from petroleum coke addressed in the study. These relationships can be seen in **Table 17** and **Chart 11**.

The difference between the emissions avoided by shifting firewood and the excess emissions from increased electricity consumption result in the total emissions avoided by the Maerz kilns using biomass in natura and torrefied biomass in the LCS. **Chart 11** shows the comparison.

Chart 13 – Lime industry: Wedge Graph



Source: Prepared by the authors (2019) based on Freitas, René Vogelaar and Renato Vogelaar (2017a).

It is concluded that the increase in emissions from electricity consumption is negligible, since the emissions shifted by the thermal efficiency of Maerz kilns is about 99 times greater in the year 2030.

For CCS, a capturing capacity of 80% of emissions from the lime production process was considered, which occurs in the five kilns planned for 2025. As shown in **Chart 12**, thanks to the use of CCS, there is an abrupt drop in process emissions — from 550,000 tCO_2 in 2024 to 109,000 tCO_2 in 2025.

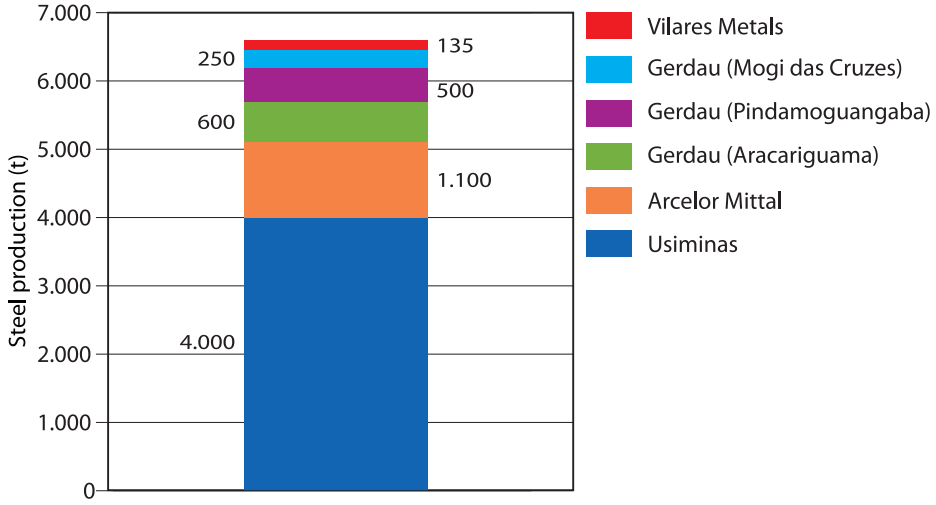
3.1.3 MACTool results from the lime industry

The emissions from the lime industry avoided from 2014 to 2030 are shown in **Chart 13**; the MAC and BECP are shown in **Table 18**.

The introduction of the three low carbon measures proposed enables generating a total reduction of 3.76 million tCO_2 in the period 2014-2030, of which 67.5% correspond to CCS. It is observed that following the introduction of CCS in 2025, emissions in the LCS become negative. This can be interpreted as the industry zeroing its emissions and still generating a surplus of GHG mitigation equivalent to about 195,000 tCO_2 in the period 2025 to 2030. In practice, this potential can be even greater if the CCS technology is used to mitigate emissions not only from processes but also from thermal energy production that are also released in the kiln. There is no doubt that if these emissions come from renewable biomass this technology can lead to negative emissions.

The MAC Curve result indicates that the most expensive measure is CCS, followed by the implementation of Maerz kilns using biomass in natura, which is slightly above torrefied biomass, with a difference of USD5/tCO_2. All measures showed a positive MAC over the entire period 2014–2030. An investment of USD94.2 million would be necessary to implement the three low carbon measures.

Chart 14 – Installed capacity of Sao Paulo's steel industry, 2013



Source: Prepared by the authors (2019) based on Freitas, René Vogelaar and Renato Vogelaar (2017b).

The BECP presents the same order of measures seen in the MAC, although with a decrease in the difference between the values. This can be explained because the CAPEXs are relatively higher for measures involving the kilns than for CCS, which makes these measures more sensitive to the IRR Benchmark. Ultimately, none of the technologies brings the return required to make them attractive, and that is why the BECP shows positive values.

It should be noted that, in practice, CCS should have MAC and BECP values higher than what is being presented in this study, since only the CO_2 capture structure in industrial plants was assessed, thus excluding the entire CO_2 transport and storage process. Further details on the limitations of the CCS study can be found in the specific report on the lime industry (FREITAS; VOGELLAR, René; VOGELAAR, Renato, 2017a).

3.2 STEEL INDUSTRY

This section presents the summary of the study developed for the steel industry in the State of Sao Paulo.

3.2.1 Baseline scenarios (BS)

The next sections present the BS developed for the steel industry in the State of Sao Paulo.

3.2.1.1 Steel production in the baseline scenario

Two production routes emerge in Sao Paulo's steel industry: the integrated route and the semi-integrated route. The difference between the two is that the integrated route involves a stage that entails reducing iron ore for producing pig iron. In this case, therefore, the significant CO_2 emission comes from the process, whereas in the semi-integrated route, which only

Table 19 – Projection for steel production in the State of Sao Paulo

Year	GDP projection	Growth rate of steel production	Integrated plant production	Semi-integrated plant production	Total steel production
	(%)	(%)	(kt/a)	(kt/a)	(kt/a)
2014	—	—	3,048	1,752	**4,800**
2015	–3.8	–5.70	2,874	1,862	**4,736**
2016	–3.0	–4.50	2,745	1,858	**4,603**
2017	1.5	2.25	2,807	1,900	**4,706**
2018	2.0	3.00	2,891	1,957	**4,847**
2019	2.0	3.00	2,978	2,015	**4,993**
2020	2.3	3.45	3,080	2,564	**5,644**
2021	2.5	3.75	3,196	2,660	**5,856**
2022	2.5	3.75	3,316	2,760	**6,076**
2023	2.5	3.75	3,440	2,863	**6,303**
2024	2.5	3.75	3,569	2,971	**6,540**
2025	2.5	3.75	3,703	3,082	**6,785**
2026	2.5	3.75	3,842	3,198	**7,039**
2027	2.5	3.75	3,986	3,318	**7,303**
2028	2.5	3.75	4,135	3,429	**7,565**
2029	2.5	3.75	4,275	3,526	**7,801**
2030	2.5	3.75	4,275	3,560	**7,835**

Source: Adapted from Freitas, René Vogelaar and Renato Vogelaar (2017b).
Note: Data: total production in 2013. All other figures are estimates.

involves the refining and mechanical transformation stage, there is a greater contribution from energy emissions (electricity consumption) (FREITAS; VOGELLAR, René; VOGELAAR, Renato, 2017b).

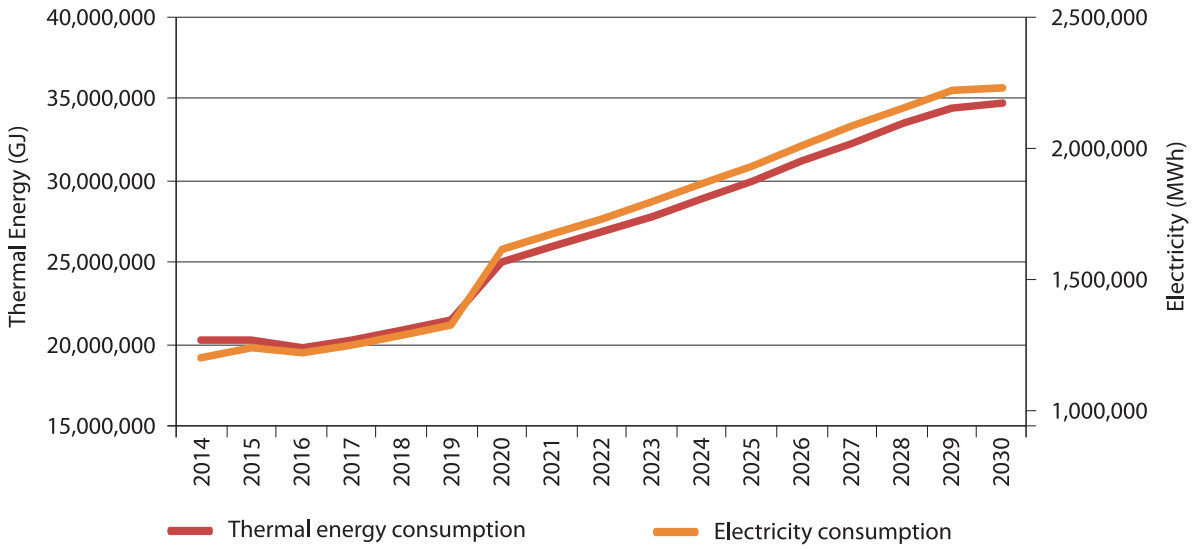
Chart 14 shows the set-up of Sao Paulo's steel industry in 2013.

To determine the growth rate of steel production (third column in **Table 19**), which was fundamental for generating emission and cost scenarios up to 2030, a scenario was established in which the steel industry outgrows Brazilian GDP by 1.5 times in a given year, based on the author's assumptions.

The total state production in 2014 was used as a basis and proportionally divided for each plant according to its installed capacity (**Chart 14**). The projection was based on each plant to facilitate modeling costs and emission in the MACTool, in order to avoid double counting emission reduction measures. It should be noted, however, that the breakdown by industrial plant (not presented in this report), or even by steel route is an estimate based on the installed capacity presented by the Brazilian Steel Institute (IABr), and therefore the figures do not represent the real production of each plant in a given year (FREITAS; VOGELLAR, René; VOGELAAR, Renato, 2017b).

An important aspect considered for projecting steel production was the increase in installed capacity. In 2014 there were 6 plants in Sao

Chart 15 – Projection for thermal energy and electricity consumption in the steel industry



Source: Prepared by the authors (2019) based on Freitas, René Vogelaar and Renato Vogelaar (2017b)

Paulo, one for the integrated route (USIMINAS) and five for the semi-integrated route. In 2015, the SIMEC plant in Pindamonhangaba began operations, with 350,000 tons per year. For 2020 there is an increase of 500,000 tons per year at the Gerdau plant in Pindamonhangaba, as well as an increase of 350,000 tons per year for SIMEC (FREITAS, VOGELLAR, René, VOGELAAR, Renato, 2017b). It was considered that in the year in which there is an increase in the installed capacity of a plant, its production is equivalent to that of the previous year, plus 60% of the increase in installed capacity. Another variable considered was the so-called "duty cycle", which limits the maximum nominal production, corresponding to 95% of the installed capacity.

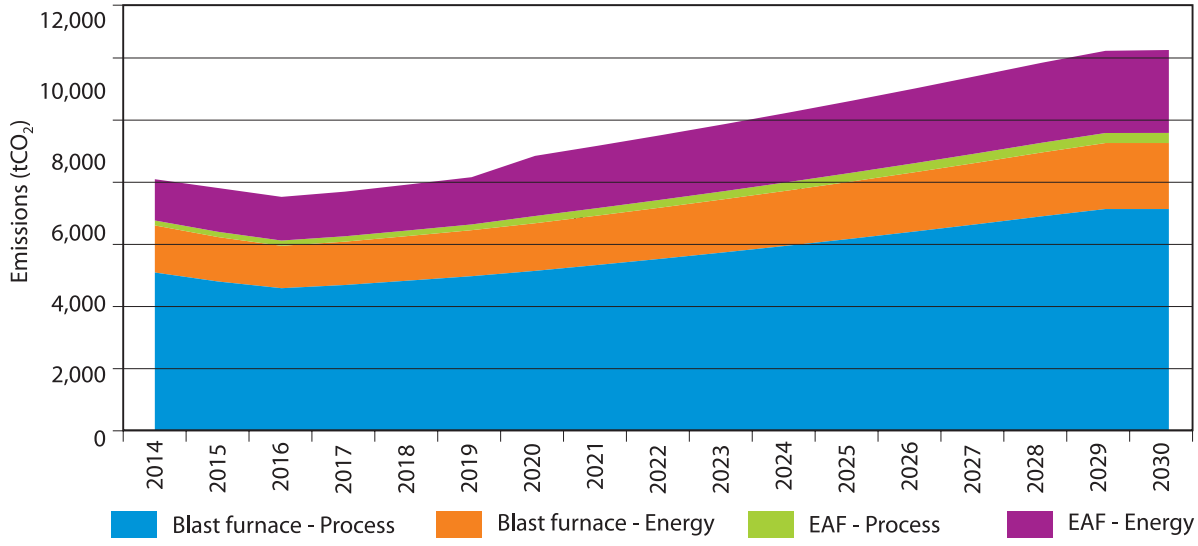
Table 19 shows that the growth of the steel industry stabilizes around 2029, when most plants reach their installed capacity. In 2014, production of the integrated route was 74% higher than that of the semi-integrated route. This ratio falls to 20% in 2030 because of the increase in the installed capacity of the semi-integrated route.

Table 20 – Scenario of emissions from the steel industry by route

Year	Integrated route		Semi-integrated route	
	Process emissions	Energy emissions (1)	Process emissions	Energy emissions (1)
	($GgCO_2$)			
2014	4,450	1,325	140	1,164
2015	4,196	1,250	149	1,236
2016	4,008	1,193	149	1,232
2017	4,098	1,220	152	1,259
2018	4,221	1,257	157	1,296
2019	4,347	1,294	161	1,334
2020	4,497	1,339	205	1,696
2021	4,666	1,389	213	1,759
2022	4,841	1,441	221	1,824
2023	5,022	1,495	229	1,891
2024	5,211	1,551	238	1,961
2025	5,406	1,609	247	2,033
2026	5,609	1,669	256	2,108
2027	5,819	1,732	265	2,185
2028	6,037	1,797	274	2,258
2029	6,242	1,857	282	2,320
2030	6,242	1,857	285	2,341

Source: Prepared by the authors (2019) based on Freitas, René Vogelaar and Renato Vogelaar (2017b)
(1) Includes electricity losses in the transmission and distribution network (Chart 6)

Chart 16 – Emissions from the steel industry in the baseline scenario



Source: Prepared from Table 20.
Note: AEF = arc electric furnace (semi-integrated route)

3.2.1.2 Energy consumption in the baseline scenario

Both the integrated route and the semi-integrated route use fuel and electricity at different proportions. In the semi-integrated route, the share of electricity in the total energy consumption balance is higher.

Chart 15 shows thermal energy and electricity consumption, adding the two steel routes. Electricity consumption in the integrated and semi-integrated route is 106 kWh/t_{steel} and 500 kWh/t_{steel} respectively. As for thermal energy consumption, the integrated route uses per ton of steel: 1.73 GJ of NG; 0.47 GJ of coke-oven gas; and 1.15 GJ of blast furnace gas. In turn, the semi-integrated route uses NG as primary fuel, at a factor of 5.70 GJ/t_{steel} (FREITAS; VOGELLAR, René; VOGELAAR, Renato, 2017b).

As the relationship between energy consumption and production is constant, the evolution of **Chart 15** follows the growth of steel production. The "step" between 2019 and 2020 is due to the increase in installed capacity for the semi-integrated route.

3.2.1.3 CO_2 emissions in the baseline scenario

Emissions in the BS by type of route and type of emission are shown in **Chart 16** and **Table 20**. Process emission factors for the integrated and semi-integrated routes are 1.46 tCO_2e/t_{steel} and 0.08 TCO_2e/t_{steel} respectively (FREITAS; VOGELLAR, René; VOGELAAR, Renato, 2017b).

Chart 16 shows the estimated emissions from the industry, which comprises process and energy consumption emissions, for the two main routes.

Integrated route alternative scenario (USIMINAS Cubatão)

In November 2015, due to a strong contraction in steel demand in the domestic market, coupled with the fact that in 2015, according to global statistics (OECD, 2016), the excess supply of steel worldwide was evident, USIMINAS, in Cubatão, shut down its blast furnace, which is responsible for the vast majority of CO_2 emissions (76.6% of all steel sector emissions in the BS), and began to operate its rolling mill facility only, importing steel from Minas Gerais.

With the shutdown of the blaster furnace, the EF of the integrated route was reduced from 1.89 to 0.27 tCO_2/t_{steel} (FREITAS; VOGELLAR, René; VOGELAAR, Renato, 2017b). Considering USIMINAS' maximum steel production of 4,275 million tons, the shutdown of the blaster furnace would imply an annual reduction of 6.9 million tCO_2. There are some indications that this blast furnace will be restarted, but if it remains shut down until 2030, about 104 million tCO_2 are expected to be avoided over a 15-year period. This represents 72% of all emissions from the steel industry in the BS.

3.2.2 Low carbon scenario (LCS)

The technologies, barriers and emissions for the steel industry in the LCS are described below.

3.2.2.1 CO_2 mitigation technologies in the low carbon scenario

In the steel industry, a low-carbon technology was considered to mitigate process emissions from the integrated route, namely the Top Gas Recycling Blend Furnace-Metildietanolamine (TGRBF-MDEA), in addition to two technologies to mitigate electricity emissions, which are the pre-heating furnace (Consteel System) and the DC furnace, both related

to the semi-integrated route. Semi-integrated route measures follow the EF and electricity costs assumptions described in sections 2.3.2 and 2.6.3 of this report.

Because these are incremental technologies, CAPEX in the LCS was also applied incrementally (low-carbon plant minus reference plant), but since it is assumed that there is an additional cost of adapting the existing infrastructure, the incremental value was multiplied by an implementation factor determined by the sector specialist for the integrated and semi-integrated routes of 1.6 and 1.4 respectively (FREITAS; VOGELLAR, René; VOGELAAR, Renato, 2017b).

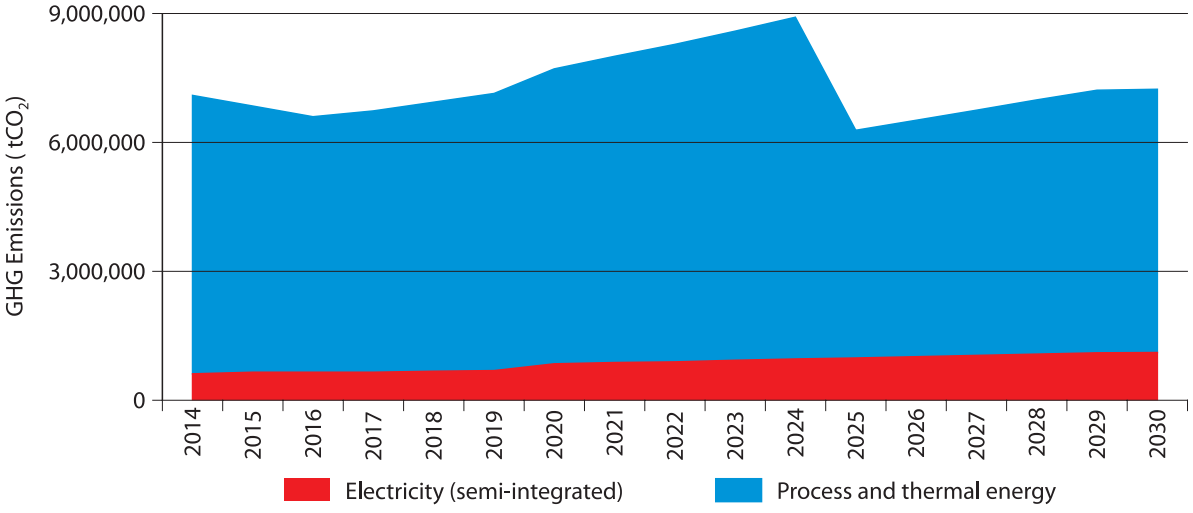
3.2.2.1.1 *Top gas recycling with methyl diethanolamine*

This is a technology for the integrated route that consists of recovering top gas from steel production blast furnaces. The technology not only reduces emissions by capturing CO_2 (as in the case of CCS, reduction of process emissions), but also recovers carbon monoxide (CO) and hydrogen (H_2), which can be reinjected, thus generating fuel savings (reduction of energy emissions) (FREITAS; VOGELLAR, René; VOGELAAR, Renato, 2017b). The cost of implementing a TGRBF-MDEA plant is USD1,219/t_{steel} — USD188.00 more expensive than the BS plant without this technology. The operational cost using the TGRBF-MDEA technology is USD330 per ton of steel against USD324/t_{steel} in the reference plant.

3.2.2.1.2 *Scrap preheating and continuous feed*

For the semi-integrated route, two elements are part of the same technology. The goal is to replace a "batch" feed system with a continuous feed system, thus avoiding energy losses due to interruptions in the furnace loading process (FREITAS; VOGELLAR, René, VOGELAAR, Renato, 2017b). The cost of implementing and operating and maintaining a plant using this technology is USD583 and USD362 per ton of steel respectively. In comparison, the implementation cost of a semi-integrated reference plant is USD576 per ton of steel and the operation and maintenance cost is the same.

Chart 17 – Steel sector: emissions in the low carbon scenario



Source: Prepared by the authors (2019) based on Freitas, René Vogelaar and Renato Vogelaar (2017b).
Note: Electricity emissions from the integrated route are not included with "electricity" as they were not subject to reduction in the LCS.

3.2.2.1.3 *Direct current electric furnace*

Another measure for the semi-integrated route is to convert the electric arc system from alternating current to direct current to ensure greater process stability, thus reducing the flicker effect, decreasing energy consumption and ensuring a homogeneous fusion around the electrodes (FREITAS; VOGELLAR, René; VOGELAAR, Renato, 2017b). The cost of setting up a plant with a DC furnace is USD584 per ton of steel — USD1 more expensive than the scrap heating plant and the same operation and maintenance cost as in the BS.

3.2.2.2 Barriers to the development of the low carbon scenarios proposed

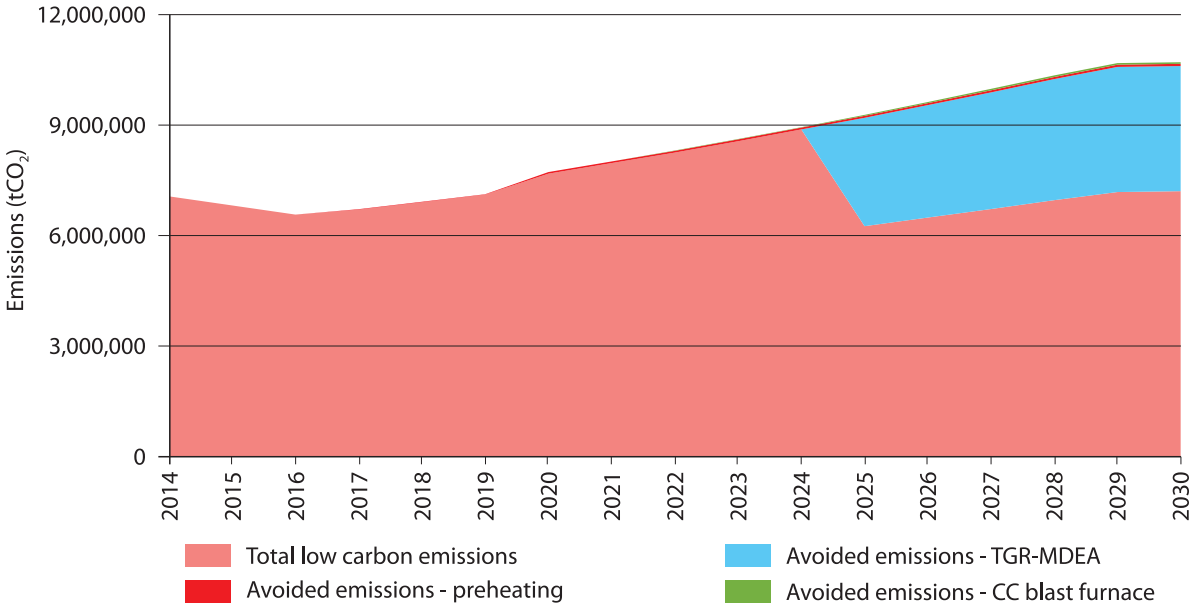
The main barriers to the LCS are the context and infrastructure of the steel industry, which has been experiencing a production crisis triggered by the economic crisis of 2008, according to the sources assessed by the consultant. According to the expert, direct and indirect imports affect the economy of this sector of Brazilian industry. It should be noted that only a strong government policy of incentives, credit lines and tax relief can motivate the steel industry to take measures to reduce CO_2 emissions.

Table 21 – Steel industry: Marginal Abatement Cost and Break-Even Carbon Price

Industry	Measure/ technology	MAC	BECP	Avoided emissions 2014–2030
		(USD/tCO_2)		(MtCO_2)
Power conservation	Preheating and continuous feed	– 134	– 288	0.61
Power conservation	Direct current furnace	– 102	– 229	0.27
Manufacturing	TGRBF-MDEA	16	95	19.27

Source: Prepared by the authors (2017) based on Freitas, René Vogelaar and Renato Vogelaar (2017b).
Note: MAC and BECP were constructed based on the results obtained from literature review and analysis by sector experts José Milton de Freitas, René Vogelaar and Renato Vogelaar.

Chart 18 – Steel sector: Wedge Graph



Source: Prepared by the authors (2019) based on Freitas, René Vogelaar and Renato Vogelaar (2017b).
Note: The Wedge Graph was constructed based on the results obtained from literature review and analysis by sector experts José Milton de Freitas, René Vogelaar and Renato Vogelaar.

As steel production has been reduced, its resumption can benefit from the leapfrog effect (benefit from more advanced technologies deployed in developed countries), which allows the technologies deployed to be the most aggressive among all low carbon technologies available worldwide (FREITAS; VOGELAAR, René; VOGELAAR, Renato, 2017b).

3.2.2.3 CO_2 emissions in the low carbon scenario

Chart 17 shows the emissions from the steel industry in the LCS (blast furnace scenario), distinguishing between process and thermal energy from electricity in the semi-integrated route.

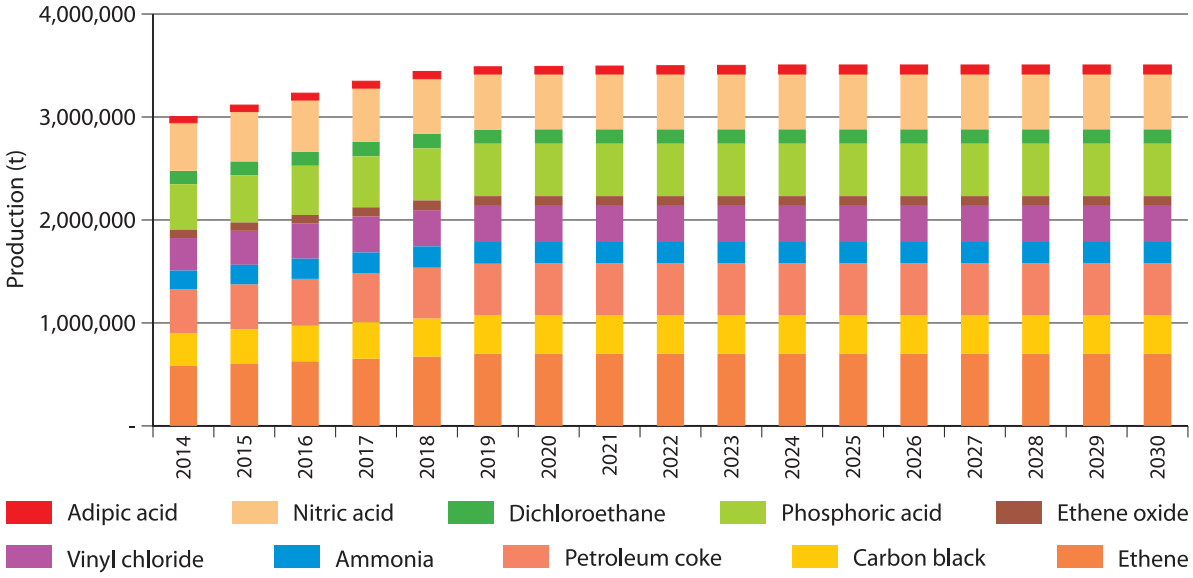
As observed in the lime industry for CCS, there is a "step" in CO_2 emissions due to the abrupt decrease caused by the TGRBF-MDEA. It is also observed that the order of magnitude of electricity emissions from the semi-integrated route is considerably smaller than that of process emissions.

3.2.3 MACTool results in the steel industry

Chart 18 shows the avoided emissions from the steel sector due to the use of low carbon technologies.

It is concluded that the contribution to CO_2 reduction of semi-integrated route technologies (preheating and direct current furnaces) is minimal, as it represents only 4% (873,000 tCO_2) in the period 2014-2030. On the other hand, the TGRBF-MDEA technology in the integrated route, even if implemented in 2025, represents 96% (19.2 million tCO_2) of avoided emissions. In total, the equivalent of 13.4% of emissions from the BS in the period 2014–2030 can be avoided in the steel industry. In 2030, emissions would reach 7.2 million tCO_2, — only 140,000

Chart 19 – Projected production of chemicals in the baseline scenario with a 3.7 growth (limited to the installed capacity)



Source: Prepared by the authors (2019) based on Fanti et al. (2019)

14. The original analysis of the energy part of the chemical industry was designed for the two growth scenarios, 2.7% and 3.7% p.a., not limited to the installed capacity.

tCO_2 above 2014 levels. However, it should be stressed that using the full potential of the TGR-BF-MDEA technology depends on the existence of conditions for the geological storage of CO_2. Furthermore, the cost for this stage was not considered in the experts' analysis.

Table 22 – Chemical industry: annual growth rates

Year	Chemical production growth (in relation to the previous year)
	(%)
2013	—
2014	3.63
2015	3.63
2016	3.63
2017	3.54
2018	2.84
2019	1.31
2020	0.11
2021	0.08
2022	0.08
2023	0.09
2024	0.09
2025	0.00
2026	0.00
2027	0.00
2028	0.00
2029	0.00
2030	0.00
Average growth (2013–2030)	1.12

Source: Prepared by the authors (2019) based on information from Fanti et al. (2017)

Table 21 shows the MAC and BECP results of low carbon technologies.

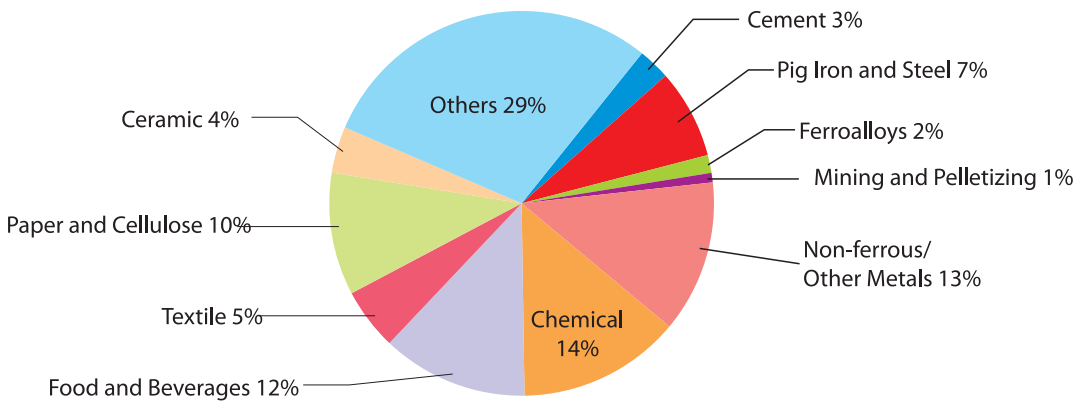
The technologies of the semi-integrated route showed substantially negative abatement cost and BECP, which means that they are interesting from an economic standpoint. However, their mitigation potential is small, meaning that in absolute terms they are not highly profitable, as total savings by 2030 do not exceed USD110 million.

The TGRBF-MDEA technology, despite its positive cost, is relatively attractive compared to the MAC of other sectors of the study, and the amount of avoided emissions is high, as previously mentioned. If the three low carbon measures were implemented, the final cost to the sector would be USD199 million by 2030 compared to the BS.

3.3 CHEMICAL INDUSTRY

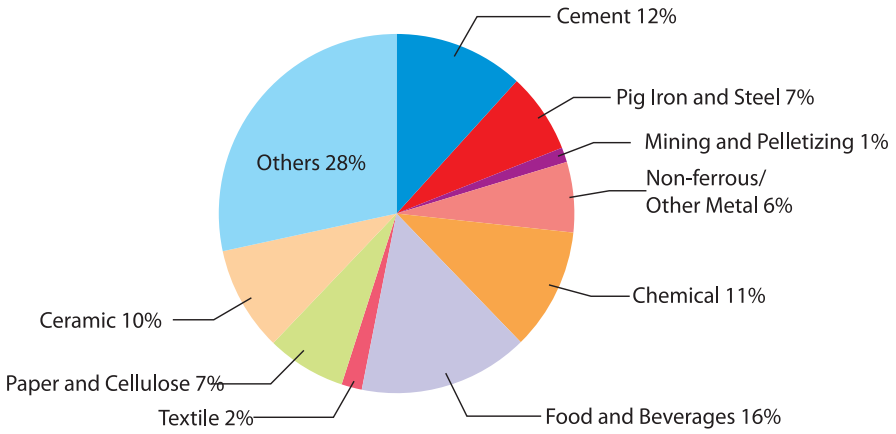
This section presents the synthesis of the study developed for the chemical industry in the State of Sao Paulo.

Chart 20 – Relative electricity consumption by sector, 2013



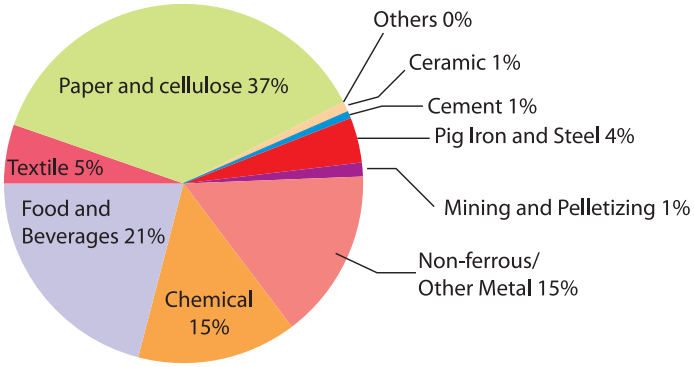
Source: Prepared by the authors (2019) based on Sao Paulo (2014).

Chart 21 – Relative consumption of natural gas and petroleum products by sector, 2013



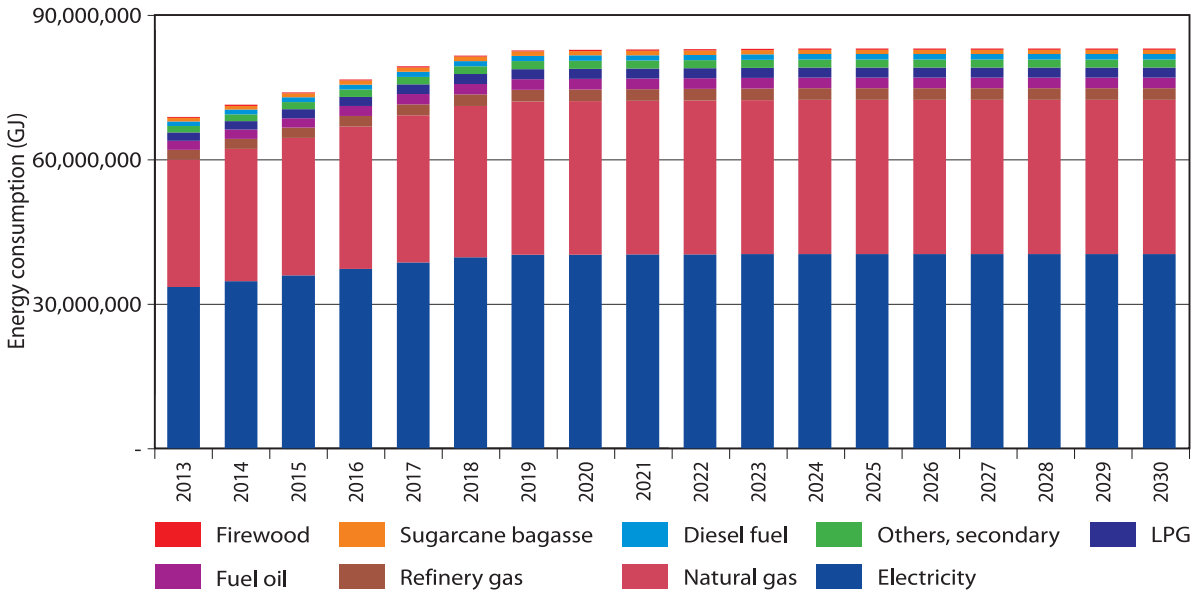
Source: Prepared by the authors (2019) based on Sao Paulo (2014).

Chart 22 – Relative fuel oil consumption by sector, 2013



Source: Prepared by the authors (2019) based on Sao Paulo (2014).

Chart 23 – Projection for energy consumption by the chemical industry



Source: Prepared by the authors (2017) based on Fanti et al. (2017)

3.3.1 Baseline scenario

The BS for chemical production, the associated energy consumption, as well as the respective emissions are described below.

3.3.1.1 Chemical production in the baseline scenario

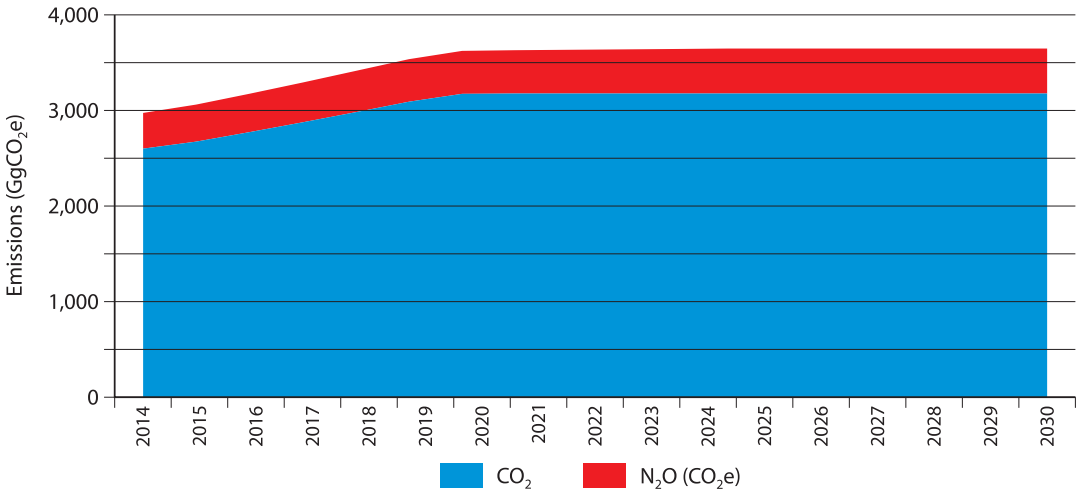
Based on the Brazilian Industrial Development Agency (ABDI) and the Federation of Industries of the State of Sao Paulo (FIESP), chemical industry consultants determined two annual growth scenarios from 2013 to 2030: 2.7% and 3.7% (FANTI et al., 2017). The project's technical coordination team decided to use the 3.7% growth to build the MAC curve[14]. It was also assumed that the maximum installed capacity

Table 23 – Greenhouse gas emission factors for the baseline scenario

Products	Emission factor (tCO_2e/t)
Adipic acid (1)	1.494
Nitric acid (1)	0.634
Phosphoric acid	0.059
Ammonia	1.300
Vinyl chloride	0.294
Petroleum coke	0.730
Dichloroethane	0.196
Ethene	1.870
Carbon black	2.620
Ethene oxide	0.863

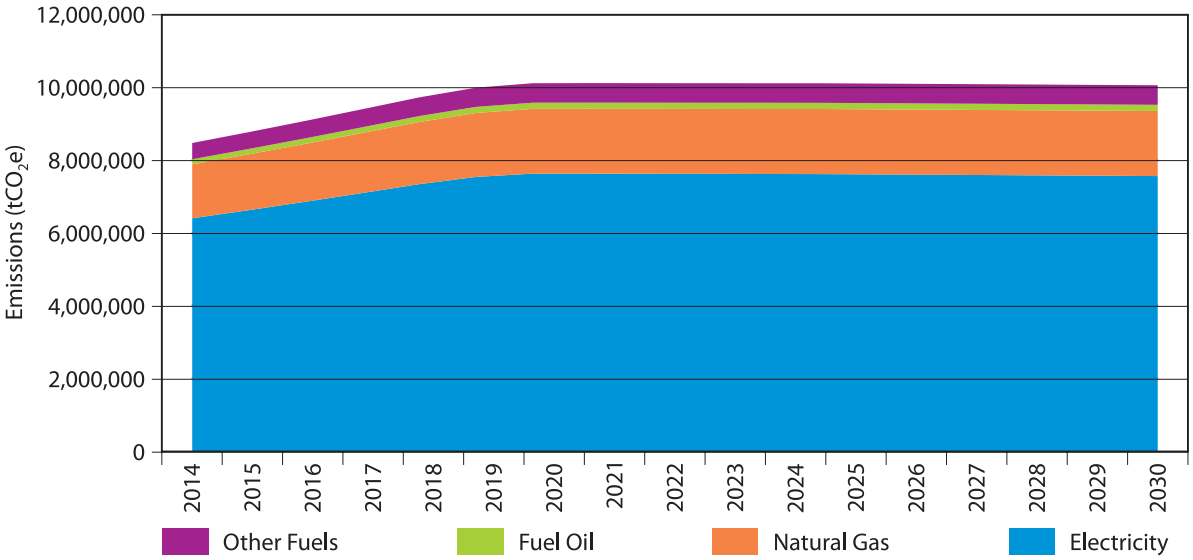
Source: Adapted from Fanti et al. (2017)
(1) Processes that emit N_2O and were converted to CO_2e.

Chart 24 – Evolution of greenhouse gas emissions from process in the chemical industry



Source: Adapted from Fanti et al. (2017)

Chart 25 – Evolution of greenhouse gas emissions from energy consumption in the chemical industry



Source: Prepared by the authors (2019) based on Fanti et al. (2019)

in 2013 will be reached by 2025, and from this year onwards growth will stagnate, as shown in **Chart 19**.

Table 22 shows the total growth in the production of chemicals between 2014 and 2030 based on the assumption that there will be no increase in the industry's installed capacity until 2030 and, therefore, growth will stagnate. Growth starts at a rate close to 3.7% p.a., but the average for the period 2014-2030 is practically 1% p.a., which is in line with the growth forecast for the Brazilian economy for 2016.

3.3.1.2 Electricity consumption in the baseline scenario

In 2013, the chemical industry ranked first in electricity consumption (14%) and third in FO consumption (15%). The first and second ranking industries in FO consumption are not covered by this study (SAO PAULO, 2014). Chart 20 shows the relative electricity consumption by sector in 2013.

Chart 21 shows the relative NG consumption by sector in 2013.

Chart 22 shows the relative FO consumption by sector in 2013.

Charts 20, **21** and **22** show the significant share of the chemical industry in the consumption of the main GHG-emitting sources. Thus, measures seeking greater efficiency in energy consumption can lead to the mitigation of a significant amount of emissions from the chemical industry.

The figures in **Table 22** were applied to energy consumption in 2013 to generate the consumption scenario presented in **Chart 23**.

3.3.1.3 CO_2 emissions in the baseline scenario

To project GHG emissions up to 2030, the EFs set by the IPCC were adopted and used in Sao Paulo's Inventory of anthropogenic emissions of direct and indirect greenhouse gases (CETESB, 2011), as shown in **Table 23**.

Chart 24 shows the evolution of process emissions, separating nitrous oxide (N_2O) from CO_2, due to its share in total emissions accounted for in CO_2e.

Chart 25, in turn, shows the evolution of emissions from energy consumption, separating the three energy vectors addressed in the project: NG, FO and electricity. It is concluded that electricity accounts for 75% of all emissions in the chemical industry in the period 2014–2030.

3.3.2 Low carbon scenario

The LCS of the chemical industry production, the barriers faced, and the respective emissions are presented below.

3.3.2.1 CO_2 mitigation technologies in the low carbon scenario

The technologies to mitigate emissions from chemical processes are: (i) deployment of a secondary nitric acid abatement technology; (ii) deployment of a technology for the recovery of H_2 from ammonia purge gas; (iii) a new industrial "bioethene" (ethanol ethane) production facility to produce vinyl chloride and ethene oxide.

The technologies to mitigate emissions from energy consumption are: (i) lighting of industrial plants using LEDs; (ii) use of more efficient motors; (iii) replacement of FO with biomass; (iv) replacement of NG with biomass; and (v) cogeneration.

3.3.2.1.1 *Nitric acid*

Nitric acid (HNO_3) is an inorganic compound used primarily in the manufacture of synthetic fertilizers, in concentrations varying from 53% to 62%. But nitric oxide (NO), an intermediate compound in the production of nitric acid, can react quickly and form N_2O, which is a GHG, as an unintended by-product. Due to the N_2O mitigation technology used in the LCS, and particularly in the production process that operates at high pressure, there is CO_2 emission from the use of the catalytic reduction technology on a high temperature platinum catalyst. The energy required to reach the desired temperature is obtained using fuel gas. Despite CO_2 emissions, the abatement consists of the transition from N_2O to CO_2, which reduces emissions due to the decrease in the respective GWP from 310 to 1 (FANTI et al., 2017). Implementation of the catalyst for N_2O abatement in nitric acid production is estimated at USD3.54 million. Because it is a technology complementary to what already exists, investments in the BC were not considered.

3.3.2.1.2 *Ammonia*

Ammonia (NH_3) is one of the basic chemicals produced in large quantities and used as a source of nitrogen. It is a raw material used to produce nitric acid. The technology is associated with the recovery of H_2 from purge gas of the ammonia synthesis system. Purge is a consequence of the increased concentration of inert, non-reactant gases in the synthesis circuit. To maintain the pressure, it is necessary to purge the system, which also contains H_2 and N_2 in addition to inert gases. This measure enables returning H_2 to the ammonia synthesis circuit as raw material, equivalent to a minimum production of 4,000 tons of ammonia per year, thus avoiding the emission of 1.30 tCO_2/tNH_3 (FANTI et al., 2017). The cost of a system for recovering H_2 from purge gas is USD3.9 million. Since it is a technology complementary to what already exists, investments in the BS were not considered.

3.3.2.1.3 *Bioethene*

Ethene (C_2H_4) is the primary hydrocarbon, one of the main substances in the petrochemical industry's value chain, used in the production of plastics, including high and low-density polyethylene and polyvinyl chloride, and as raw material for manufacturing vinyl chloride, ethene

oxide, dichloroethene and ethylbenzene, used in the production of styrene. The mitigation opportunity in the LCS is associated with the use of a renewable raw material, i.e. "green" ethene. The reduction, therefore, will not occur in ethene production, since the production of petrochemical ethene remains the same as in baseline scenario, but in the production of vinyl chloride and ethene oxide (FANTI et al., 2017), in which raw material from a carbon neutral source is used as the result of the emissions reabsorbed in the planting of biomass (see section 2.3.3).

The cost of a bioethene production plant (FANTI et al., 2017) is about USD370 million, while the cost of a petrochemical ethene plant used in the BS is about USD238 million. Although CAPEX is higher in the LCS, the variable with the highest weight in the MAC value is the cost of the raw material (ethanol), which is on average 148% higher in the LCS, due to the price of ethanol. This type of technology is already being used by a plant located in Rio Grande do Sul. In addition, revenue from the sale of petrochemical ethene and bioethene was also considered. It was assumed that bioethene would be sold at a price 30% higher than that of petrochemical ethene. Therefore, the sale prices per ton are USD1,800 for bioethene and USD1,385 for petrochemical ethene.

3.3.2.1.4 *LED lamps*

LED is a technology that provides more energy efficiency compared to traditional lighting used in chemical plants, which is predominantly comprised of fluorescent lamps. LED lighting has the potential to reduce electricity consumption by 36.6% (FANTI et al., 2017). The cost of installing LED lamps was estimated by the authors (FANTI et al., 2017) at USD800/MWh, while traditional lighting was estimated at USD132/MWh.

3.3.2.1.5 *More efficient motors*

The energy consumption by high efficiency motors to be used in the LCS is on average 11.7% lower when compared to traditional motors (FANTI et al., 2017). An important consideration is that because motors are a similar technology, the operation and maintenance costs are the same in both scenarios. That is why the difference between the two scenarios (BS and LCS) is considered null when they are input in the MACTool. The cost of high efficiency motors is USD6/MWh. As it is a technology complementary to what already exists, the deployment cost in the BS was considered equal to zero.

3.3.2.1.6 *Fuel oil*

The replacement of CO with biomass seeks to reduce emissions to zero by 2020, the year in which penetration of the technology will reach 100%, according to the literature surveyed by the industry expert (FANTI et al., 2017). The biomass to be used is renewable eucalyptus wood. Initially, the idea was to use sugarcane bagasse because its price is basically half that of firewood, according to Table 10, which shows the equivalence factors of fuels. However, bagasse would not be available due to its seasonality and competition for electricity generation in the State of Sao Paulo.[15]

15. The sugarcane bagasse issue was raised by FIESP technicians in a meeting with project members on June 23, 2015.

The implementation cost of an FO boiler is USD5.18/GJ, while a biomass boiler costs twice as much, i.e. USD10.39/GJ.

3.3.2.1.7 *Natural gas*

The substitution of NG follows basically the same principles as the previous technology, except for the fossil EF to be shifted (see Table 1) and the fact that penetration only reaches 20% of substitution of the total NG consumed until 2030.

Because the equipment in both cases is similar, the authors considered the same deployment cost as the previous technology in the BS and the LCS — USD5.18/GJ and USD10.39/GJ respectively (FANTI et al., 2017).

3.3.2.1.8 *Cogeneration*

Cogeneration consists of using the NG that was not replaced with biomass (previous measure) in electricity generation (FANTI et al., 2017). This is the most promising energy-related measure in the chemical industry, since it is not only the measure with the greatest potential (52.6% of the overall reduction in the LCS, see section 3.3.3), but it also yields extra revenue from the sale of generated electricity to the network. It is important to point out that the measure does not reduce NG emissions, since this reduction is due to the biomass-related measure. The reduction refers to the emissions avoided from electricity generation, considering the factor of 588.4 gCO_2/ kWh. That is, emissions from NG combustion continue to occur, but part of the energy released is used to produce electricity, in addition to the heat that already used to be consumed by the chemical industry. That is, emissions from NG combustion are allocated to the heat that already used to be demanded by chemical processes in the BS. In the BS, the deployment cost is the same as previously mentioned for the GN and FO measures — USD5.18 / GJ — because the technology is the same. In the LCS, a cogeneration boiler has an implementation cost of USD15.11/GJ.

3.3.2.2 Barriers to the development of the low carbon scenarios proposed

For mitigation technologies related to chemical processes, there are both barriers and opportunities for each product addressed (FANTI et al., 2017).

The opportunity for ammonia production is associated with the recovery of H_2 from purge gas of the ammonia synthesis system. Purge is a consequence of the increased concentration of inert, non-reactant gases in the synthesis circuit. To maintain the pressure, it is necessary to purge the system, which also contains H_2 and N_2 in addition to inert gases. This measure enables returning H_2 to the ammonia synthesis circuit as raw material, equivalent to a minimum production of 4,000 tons of ammonia per year, thus avoiding the emission of 1.30 tCO_2/tNH_3 (FANTI et al., 2017). The biggest barrier is the investment in the mitigation technology for the recovery of H_2 from purge gas of the ammonia synthesis system.

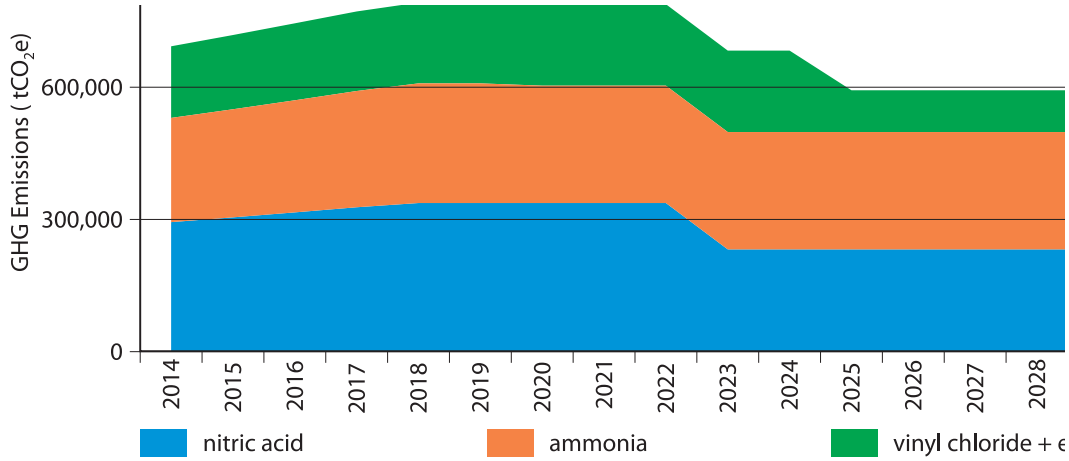
The production of nitric acid is associated with the use of an emission abatement technology described by the Methodology for the breakdown of N_2O into nitric acid production units. The main barrier to this measure is the

cost of installing and operating the nitrous oxide destruction system.

For ethene production, it was found that the mitigation opportunity for the LCS is associated with the use of alternative raw materials, i.e. NG and ethanol from renewable sources. The main barrier is raw material, i.e. petrochemical naphtha used in the production unit located in Sao Paulo. The processing of raw materials — petrochemical naphtha, NG and ethanol — has different profiles for producing petrochemical derivatives.

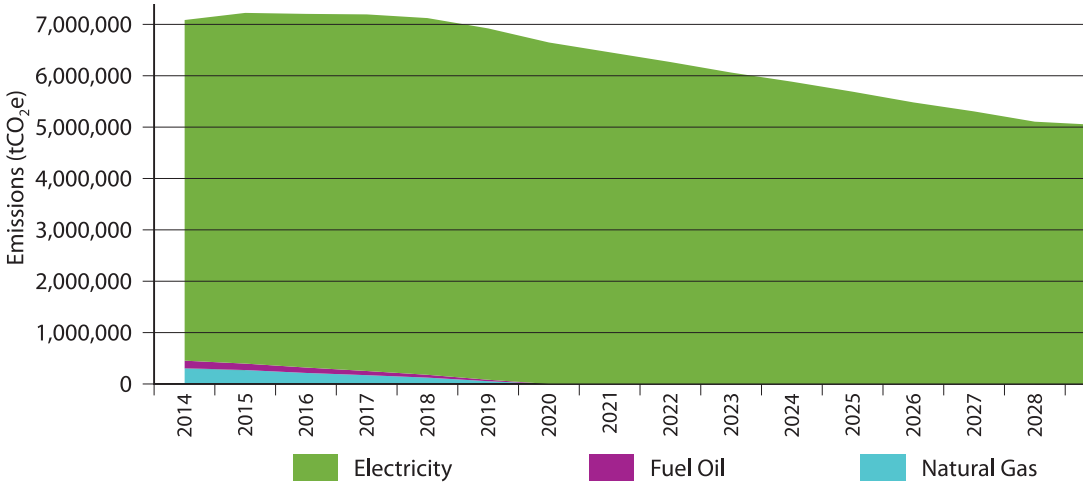
In the area of energy, there are also opportunities and barriers for implementing the LCS.

Chart 26 – Low carbon scenario: emissions from chemical processes



Source: Prepared by the authors (2017) based on Fanti et al. (2019).

Chart 27 – Low carbon scenario: emissions from energy consumption in the chemical industry



Source: Prepared by the authors (2019) based on Fanti et al. (2017).
Notes: NG emissions do not reach zero in 2020. Part of these emissions are allocated to the electricity sector, due to cogeneration.

16. The chemical and energy products presented are only those that are the target of project measures and therefore contribute to the reduction of emissions. The other chemical and energy products shown in the BS are not included in Chart 26 and Chart 27, as they do not change.

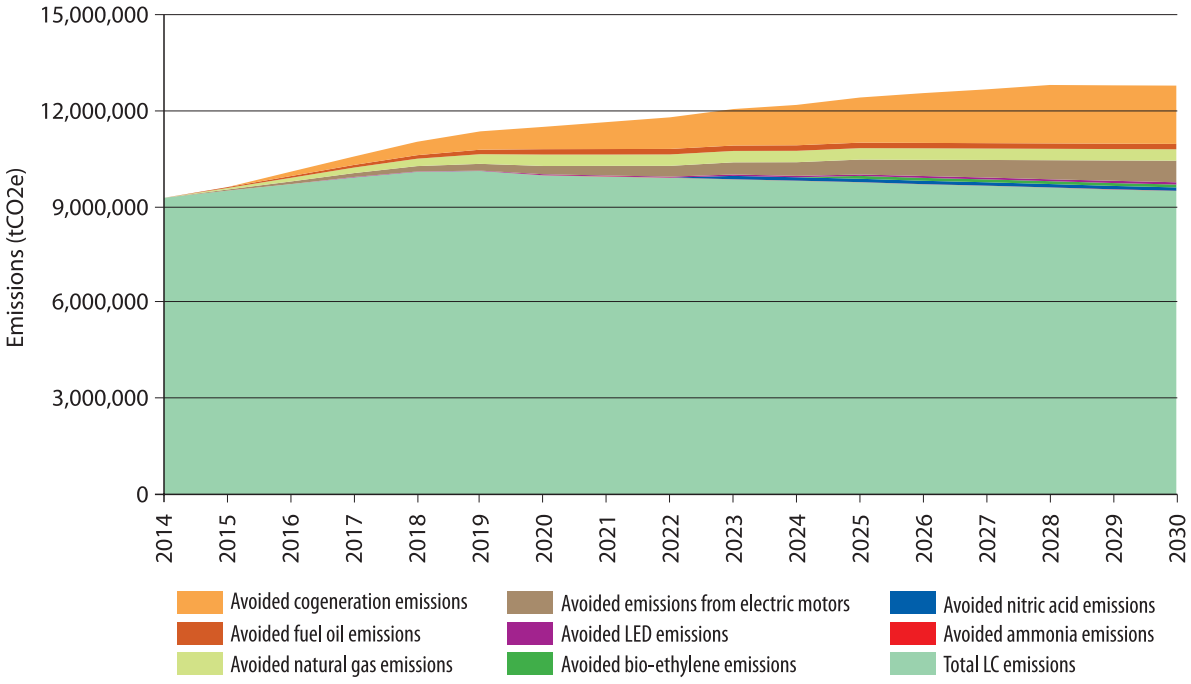
Reducing electricity consumption, for example, reduces not only GHG emissions but also energy costs, resulting in a "win-win" situation. The biggest barriers are related to the initial costs of deploying and operating the technologies, although the economic analysis shows that they are amortized during the life cycle of these technologies.

Like energy efficiency, cogeneration leads to environmental and economic gains by reducing thermal energy losses in the fuel-burning process. Many companies now produce their own electricity by harnessing energy from their processes, and when generation is greater than self-consumption, these companies can sell this surplus to the network and generate revenue.

In the case of the substitution of fossil fuels for reforestation wood, we have the use of renewable fuels from biomass that have neutral emission within the carbon cycle (DONG et al., 2006). One of the barriers is that the burning of firewood results in the emission of particulate matter and other pollutants regulated by law. However, there are technologies available to solve this problem. There is also the issue of availability of planted area and variability in climate conditions to ensure the energy supply needed to replace fossil energy, as well as other environmental impacts not assessed by the study.

Considering ethanol instead of firewood, the barrier is the supply of ethanol, which changes during the year due to the seasonality of sugarcane, which also affects the price of this fuel. Research into second-generation (2G) ethanol seems to be very promising to address this supply limitation. In addition, there is a potential for increasing bioelectricity production in sugarcane mills, which can also be delivered to the electrical network.

Chart 28 – Chemical industry: Wedge Graphs



Source: Prepared by the authors (2019) based on Fanti et al. (2017)

Table 24 – Chemical industry: Marginal Abatement Cost and Break-Even Carbon Price

Sector	Measure/ Technology	MAC	BECP	Avoided emissions 2014–2030
		(USD/tCO_2)		($MtCO_2$)
Power Conservation	More efficient engines	–150	–224	5.77
Power Conservation	LED	–145	–224	0.57
Power Generation	Cogeneration	–111	–250	16.46
Fossil	Replacement of NG with reforestation wood	–75	–131	4.79
Fossil	Replacement of FO with reforestation wood	–58	–103	2.28
Manufacturing	Ammonia	–27	10	0.06
Manufacturing	Nitric acid	2	31	0.84
Manufacturing	Bioethene	1,174	3,907	0.54

Source: Prepared by the authors (2019) based on Fanti et al. (2017).
Note: The MAC and BECP were constructed based on the results obtained from literature review and the analysis by sector experts Obdúlio Diego Fanti, Jhonathan F. de Souza, Roberto Strumpf, and Natália Kurimori.

3.3.2.3 CO_2 emissions in the low carbon scenario

CO_2 emissions from both processes and energy in the LCS[16] are represented in **Chart 26** and **Chart 27** respectively.

The results were obtained considering the EF of the substances corresponding to each of the three low carbon measures. It is worth remembering that the emissions of vinyl chloride + ethene oxide (green area) are associated with the implementation of the bioethene measure. **Chart 27** shows emissions from energy consumption.

The results were obtained considering the gradual substitution of NG and OC for firewood (neutral emission) and the electricity savings resulting from the efficiency of electric motors, LED lamps and cogeneration.

Ethanol as a substitute for fuel oil and natural gas

In response to the request of representatives of the Brazilian Chemical Industry Association (ABIQUIM), a parallel analysis was performed in which FO and NG are substituted for ethanol (FANTI et al., 2017).

The price of alcohol is higher than the price of firewood and other fuels (Table 10); however, it has some advantages: because it is a liquid fuel, it is assumed that the furnaces are the same and, therefore, the CAPEX and OPEX difference from the LCS to the BS is equal to zero. Unlike biomass, ethanol does not emit particulate matter and other regulated pollutants, thus showing a concern with human health rather than just with climate change mitigation.

The MAC results for the substitution of FO and NG for ethanol are USD226/tCO_2 and USD315/tCO_2 respectively, and the BECP results are USD483/tCO_2 and USD673/tCO_2 respectively. It should be noted that because fuel price is the main cost constraint, the MAC with the substitution for ethanol for these measures is on average USD338 more expensive than that of substitution for firewood, as shown in Table 24.

3.3.3 MACTool results from the chemical industry

This section presents the modeling results for the chemical industry. As can be seen in **Chart 28**, the measures related to the increase in energy conversion efficiency and to the substitution of the energy source are the ones that entail the most significant reductions in GHG emissions.

The measure with the greatest potential in the chemical industry is the cogeneration measure, with a total of 16.5 million tCO_2 avoided in the period 2014-2030. This measure is also highly attractive because it has a negative MAC, as will be seen next. On the process side, the most promising measure is the one related to nitric acid, with 843,000 tCO_2e avoided. This is due to the great heating potential embedded in N_2O, the GHG that is the target of this measure.

Considering all technologies, the ones aimed at reducing emissions from energy represent 95% of the total mitigation in the period. This is an area of great opportunity for the implementation of low carbon alternatives.

Table 24 shows the MAC and BECP results.

The lowest cost measure is the implementation of more efficient motors, with negative USD 150/tCO_2. However, in absolute terms, the cogeneration measure is the most profitable because it would generate revenue of USD 1.8 billion in relation to the BS in the period 2014–2030, due to the large amount of CO_2 emissions avoided.

It is observed that the bioethene technology has a very high MAC (USD 1,174 / tCO_2) due to the high cost of raw material — ethanol —, which becomes the major constraint of the MAC and BECP, because of both the amount consumed per ton of bioethene and the price of ethanol. The two sensitivity analyzes performed showed that for the MAC of this measure to be close to zero, either the price of ethanol should be some 44% lower than that projected in this study (**Table 10**) or bioethene should be sold at a price 123.5% higher than that of conventional ethene (FANTI et al., 2017).

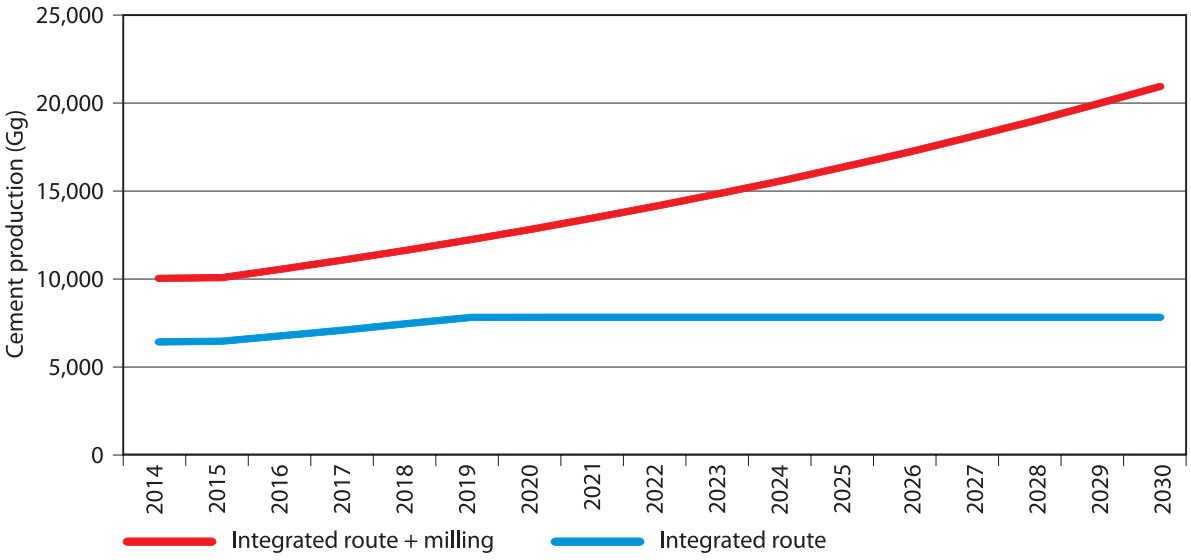
If all technologies were adopted, the result of this initiative by Sao Paulo's chemical industry would correspond to a savings of USD 2.63 billion by the year 2030.

Table 25 – Projected cement production and consumption in the State of Sao Paulo

Year	Cement production (integrated route)	Total cement production (integrated + milling only)
	(Gg)	
2014	6,413	10,020
2015	6,441	10,064
2016	6,763	10,567
2017	7,101	11,096
2018	7,457	11,651
2019	7,800	12,233
2020	7,800	12,845
2021	7,800	13,487
2022	7,800	14,161
2023	7,800	14,869
2024	7,800	15,613
2025	7,800	16,393
2026	7,800	17,213
2027	7,800	18,074
2028	7,800	18,978
2029	7,800	19,926
2030	7,800	20,923

Source: Prepared by the authors (2019) based on Punhagui et al. (2017)

Chart 29 – Projected cement production and consumption in the State of Sao Paulo



Source: Prepared by the authors (2019) from values on Table 25.

3.4 CEMENT INDUSTRY

This section presents the summary of the study developed for the cement industry in the State of Sao Paulo.

3.4.1 Baseline scenarios

The BS of cement production, associated energy consumption and consequent emissions are discussed in the following topics.

3.4.1.1 Cement production in the baseline scenario

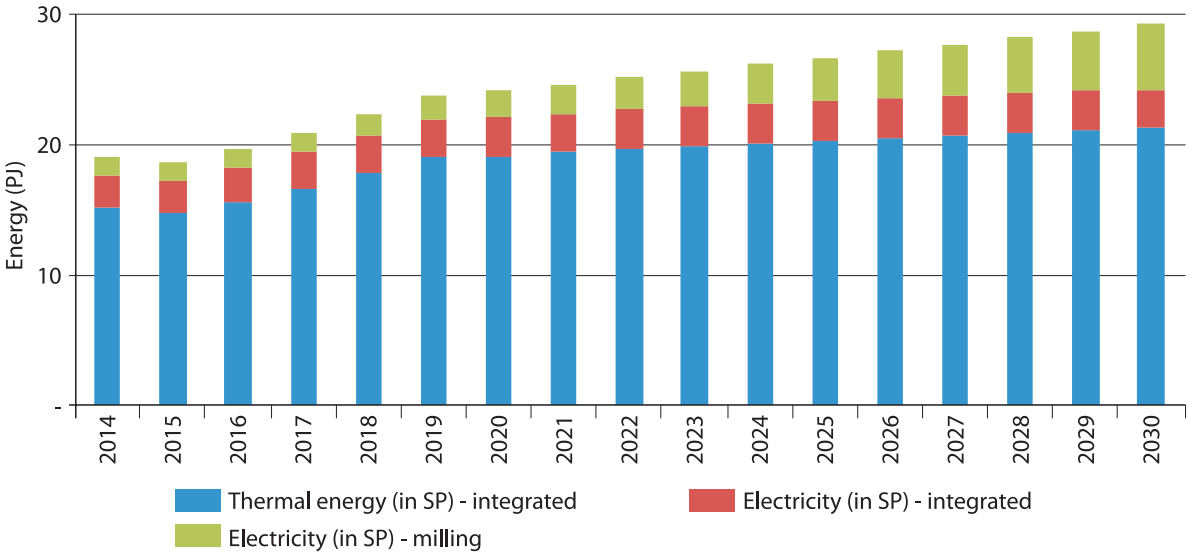
For the projection of cement production, an increase of 5% p.a. was adopted, except for 2014 and 2015, where a rate of 0.4% p.a. was used according to the National Union of Cement Industries (SNIC). There are more conservative as well as more optimistic estimates, ranging from 3% p.a. to 8% p.a. It was considered that when the installed capacity of the integrated plants in Sao Paulo is reached, growth would continue through the expansion of mills (PUNHAGUI et al., 2017). These mills import clinker from out of state and only grind the product in the state to produce cement.

Cement production (integrated route and milling) in the state is shown in **Table 25** and **Chart 29**.

Chart 29 shows the cement production and consumption in the state from 2014 to 2030.

The installed capacity of the integrated route, where decarbonation occurs for clinker production and milling, corresponded to 7.8 million tons of cement, or 64% of the state's total production in 2013 (PUNHAGUI et al., 2017). Production via the integrated route grows in this proportion until it reaches the capacity of 7.8 million and then stagnates starting from 2019. The difference between total production and production via the integrated route represents the amount of cement in which most

Chart 30 – Energy consumption for cement production in the State of Sao Paulo



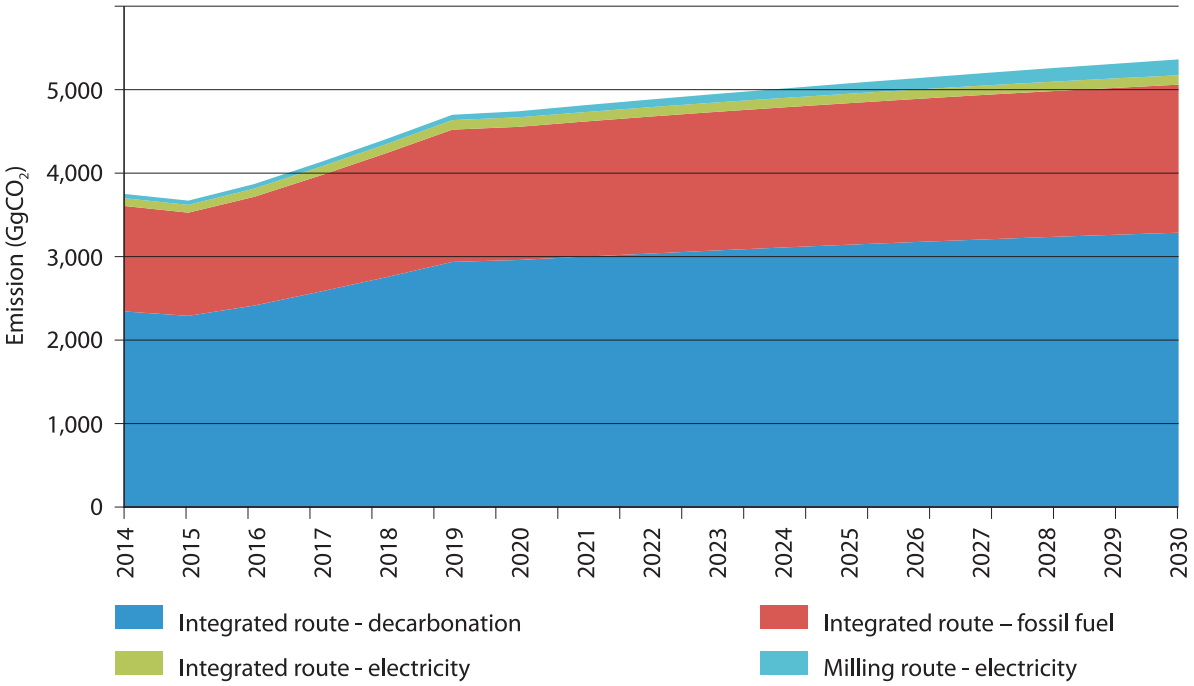
Source: Prepared by the authors (2019) based on Punhagui et al. (2019)

Table 26 – Variation in clinker content and emissions per ton of clinker and cement in the baseline scenario

Year	Fraction				Emission	
	Clinker	Filler	Slag	Gypsum	Clinker	Cement
	(%)				(tCO_2/t)	
2014	66%	4%	27%	4%	0.848	0.562
2015	64%	6%	26%	4%	0.848	0.546
2016	65%	7%	25%	4%	0.848	0.548
2017	66%	7%	24%	4%	0.848	0.558
2018	67%	7%	23%	4%	0.848	0.567
2019	68%	7%	22%	4%	0.848	0.576
2020	69%	7%	21%	4%	0.848	0.585
2021	70%	7%	20%	4%	0.848	0.593
2022	71%	7%	19%	4%	0.848	0.600
2023	72%	7%	18%	4%	0.848	0.607
2024	72%	7%	17%	4%	0.848	0.614
2025	73%	7%	16%	4%	0.848	0.621
2026	74%	7%	15%	4%	0.848	0.627
2027	75%	7%	15%	4%	0.848	0.633
2028	75%	7%	14%	4%	0.848	0.639
2029	76%	7%	13%	4%	0.848	0.644
2030	77%	7%	13%	4%	0.848	0.649

Source: Adapted from Punhagui et al. (2017)

Chart 31 – Total emissions from cement production in the State of Sao Paulo by source of emission



Source: Adapted from Punhagui et al. (2017)

of the CO_2 emissions from production do not occur within the territorial limits of the State of Sao Paulo, because limestone is being decarbonated in other states and only ground in Sao Paulo, that is, emissions in Sao Paulo are due to electricity consumption by this route.

3.4.1.2 Energy consumption in the baseline scenario

Thermal energy consumption per ton of cement varies due to its composition and the conditions of industrial processes, because the higher the clinker content in cement the greater the thermal energy required to produce it. In turn, electricity consumption for cement production is constant and corresponds to 107 kWh/t. Since the electricity used in milling is low (32 kWh/t) and heavily influenced by what is ground, due to uncertainties it was assumed that the electricity demand will not be affected in the future.

In 2013 the total amount of energy (thermal and electric) used per ton of cement was 2.74 GJ, with about 86% corresponding to thermal energy and 14% to electricity (PUNHAGUI et al., 2017).

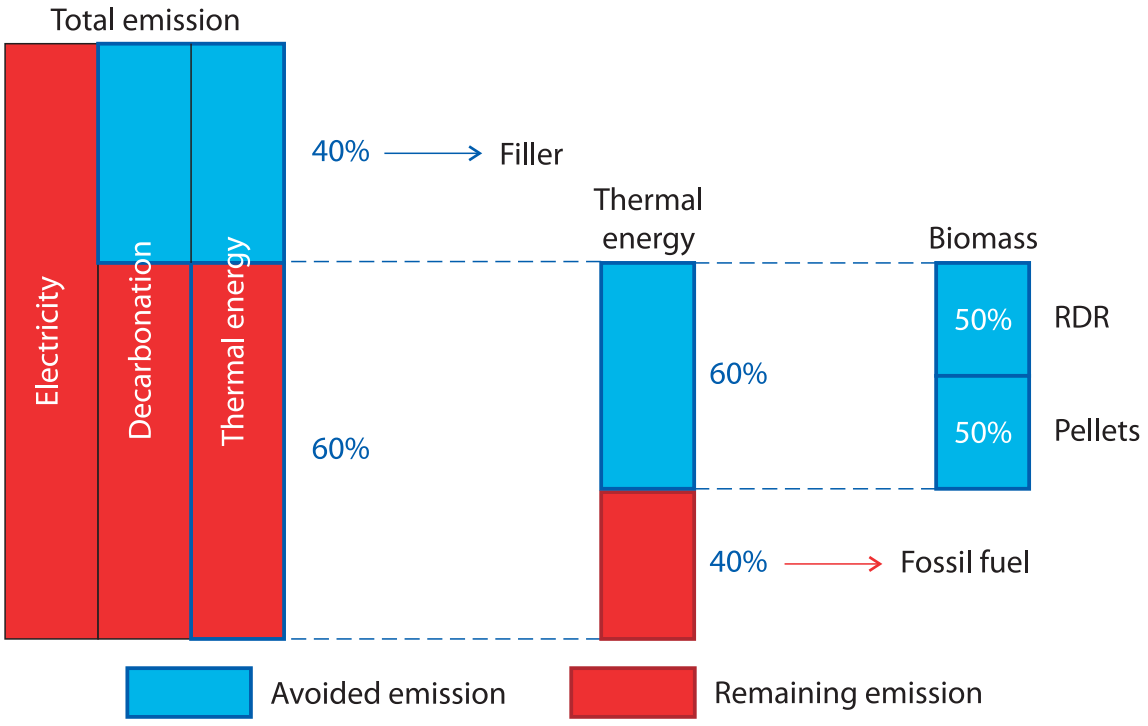
Chart 30 shows thermal energy and electricity consumption in cement production.

3.4.1.3 CO_2 emission in the baseline scenario

The EF of cement was calculated year by year in the BS, since it varies according to the clinker content in cement. The clinker EF is considered constant, corresponding to 0.848 tCO_2/t_{cement}, and the cement composition is presented in **Table 26**. From these data it is possible to arrive at the emission per ton of cement, shown in the last column of the table.

Chart 31 shows total emissions from cement production in Sao Paulo. To calculate

Figure 9 – Distribution of total emissions from the cement industry



Source: Prepared by the authors (2019) based on Punhagui et al. (2017)

emissions from cement, the data on **Table 26** and the cement production via the integrated route shown in **Table 25** were considered. To calculate electricity emissions in the cement sector, the production of both routes (integrated and milling), electricity consumption per ton of cement and the EF of electricity for inventories were considered.

3.4.2 Low carbon scenarios

The technologies, barriers and emissions in the LCS for the cement sector are presented below.

3.4.2.1 CO_2 mitigation technologies in the low carbon scenario

A total of three mitigation measures were considered for the cement industry. Measures related to emission reduction by substituting fossil fuels for RDF and wood pellets are part of the energy scope. In turn, the measure related to the increase in filler content to the detriment of clinker in cement is related to the reduction of emissions from the decarbonation process and fuel burning. Emissions from electricity consumption remain unchanged in the LCS in relation to the BS.

Fuel measures would be applied on the clinker portion that was not substituted for filler to avoid double counts between measures. This distribution is explained in **Figure 9**.

3.4.2.1.1 *Refuse-derived fuel*

Municipal Solid Waste (MSW) was used to replace part of the petroleum coke in the LCS. There are several ways to use MSW, including coprocessing and incineration. These procedures are already known and used in the sector.

The efficiency of this measure is even greater when waste is transformed into RDF. Like biomass, the EF of RDF is neutral, according to the literature and technical standards surveyed by the authors (PUNHAGUI et al., 2017).

In addition to reducing emissions from fossil fuel substitution in the cement industry, a possible methane emission (heating value nearly 30 times greater than CO_2) of this waste in landfills will be abated. Although we believe in the great potential that this phenomenon represents, the reduction of methane emissions was not considered in this study. Emissions from RDF processing were not accounted for either (PUNHAGUI et al., 2017).

As for the use of RDF as a mitigation measure, no implementation or operational costs were identified. Regarding energy costs, the prices used were those of RDF and petroleum coke (Table 10) multiplied by their respective shares in the total energy balance.

3.4.2.1.2 *Eucalyptus wood pellets*

Pellets were the second possibility presented in the sectoral analysis. Like RDF, emission from pellets is zero because it comes from renewable matter. Emissions from pellet processing were not considered either. The division of the fossil energy to be replaced between RDF and pellets was 50%–50% (PUNHAGUI et al., 2017).

Like in the previous measure, there is no CAPEX or OPEX for the pellet measure. The price of pellets and the price of petroleum coke used to determine energy costs in both the LCS and BS, respectively, can be seen in Table 10 of this study.

3.4.2.1.3 *Introduction of filler in cement*

The main raw material of cement is ground clinker. However, calcination for clinker production is largely responsible for CO_2 emissions from the cement industry.

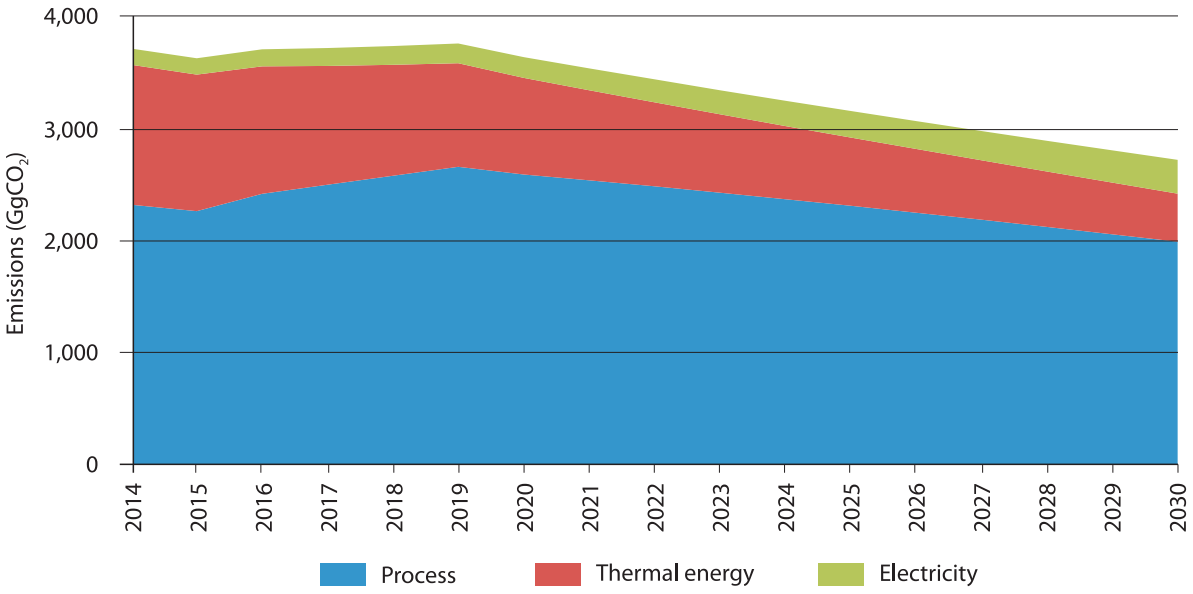
The BS estimates that the percentage of clinker in cement will increase concomitantly with the emission, as there will be no increase in slag content over the years, and the increased demand for cement will necessarily lead to an increase in clinker content (PUNHAGUI et al., 2017). In the LCS, the idea is to replace this material with filler and clay. The experts responsible for the sector proposed a scenario in which filler reaches 40% of the cement by 2030, while clinker falls to 46% or 20% less than in 2013 (PUNHAGUI et al., 2017). The cost of setting up a new mill, considering the expansion through the milling route alone, was estimated at USD 87.5 million, an amount that is used in both the BS and the LCS. The difference for the filler measure lies in the acquisition of storage silos, whose cost was estimated at USD103,700 for each 2 units (PUNHAGUI et al., 2017).

3.4.2.2 Barriers to the development of the low carbon scenarios proposed

The barriers to the LCS in the cement industry (PUNHAGUI et al., 2017) are as follows:

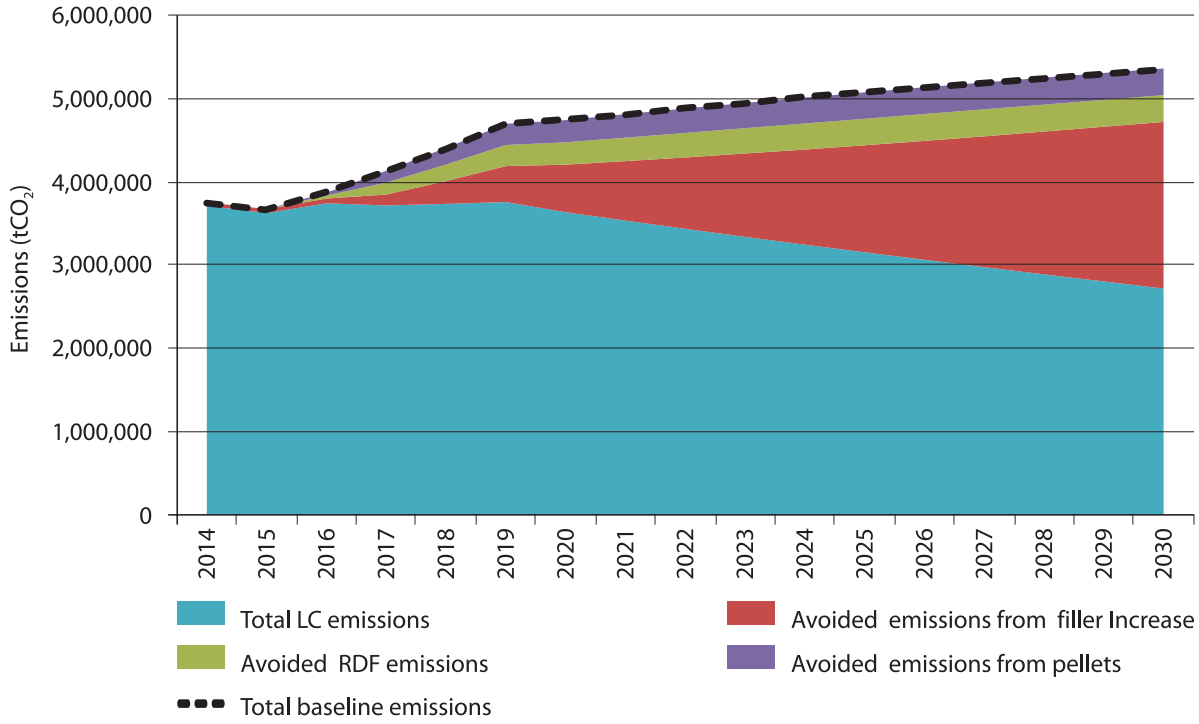
- [illegible]
- [illegible]
- [illegible]
- [illegible]

Chart 32 – Cement and construction industry: low carbon emissions



Source: Prepared by the authors (2019) based on Punhagui et al. (2017)

Chart 33 – Cement and construction industry: Wedge Graph



Source: Prepared by the authors (2019) based on Punhagui et al. (2017).

Table 27 – Cement and construction industry: Marginal Abatement Cost and Break-Even Carbon Price

Type of MACTool approach	Technology/ measure	MAC	BECP	Avoided emissions 2014–2030
		(USD/tCO_2)		($MtCO_2$)
Manufacturing	Filler	–2	–5	15.14
Fossil	Pellets	10	23	4.03
Fossil	RDF	11	24	4.03

Source: Prepared by the authors (2019) based on Punhagui et al. (2017).

■ [illegible]

3.4.2.3 CO_2 emission in the low carbon scenario

In the LCS of the cement industry, emissions gradually fall as mitigation strategies are introduced. A variation in emissions is observed until 2019 due to the production growth rates

4 Mitigation potential of Sao Paulo's industrial sectors

adopted, and from 2020 the emissions fall at an average rate of –2.9% p.a. until 2030. This can be seen in **Chart 32**, which also shows that the emission of 2.7 million tCO_2, or 994,000 tons less than 2014 levels will occur in 2030.

3.4.3 MACTool results from the cement sector

Chart 33 shows the evolution of emissions avoided by the introduction of LCS strategies in the cement industry.

It is observed that 23.1 million tCO_2 can be reduced with the implementation of BC measures or 36% of total emissions from the BS by the year 2030. The measure related to the introduction of filler in cement has the greatest mitigation potential, representing 65.3% of the total CO_2 avoided, followed by measures to replace fossil fuels, CDR and pellets, with 17.4% each.

As shown in **Table 27**, the measure of replacing clinker with filler shows a negative MAC and BECP, which makes it economically attractive. This was because the savings in OPEX and energy cost covered the initial CAPEX, yielding returns throughout the period of analysis.

The measures that replace coke with pellets and RDF show a positive cost and a mitigation potential that is practically half that of the filler. There is no CAPEX or OPEX costs to increase biomass. For this reason, the determinant of the MAC and BECP is only the difference between the prices of renewable fuels in relation to petroleum coke.

In absolute terms, the industry would spend USD55.3 million to reach the total potential of 23.2 $MtCO_2$ avoided. This amount includes the USD28.1 million saved with the filler increase.

This last section presents the results obtained in the modeling of the MACTool, in which all mitigation measures and discussions of these results are consolidated. The greatest difficulties faced throughout the development of the study and recommendations for future studies are also presented.

4.1 RESULTS

From the input data, the MACTool enables visualizing several developments such as investment intensity, energy consumption and carbon rate charts among others. However, for purposes of the study, the results of the MAC Curve, the Incremental BECP curve,[17] as well as the charts that enable visualizing GHG emissions avoided during the period 2014–2030, called Wedge Graphs, are discussed. An investment chart, which is another result of relevance to the study, is also presented.

4.1.1 Wedge Graphs for the State of Sao Paulo

Table 28 lists the 17 low carbon technologies modeled in the MACTool tool, classified by industry.

Chart 34 shows the emissions avoided in the period 2014–2030 for Sao Paulo's industry.

The most significant emission mitigation potential is that of avoided emissions from the chemical industry, which represent 39.9% of the total mitigation potential assessed by this report. As already seen in Section 3.3.3, 95% of this potential is owed to the energy area. The cement industry[18] ranks second, with 29.6% of the total emissions avoided by Sao Paulo's industry.

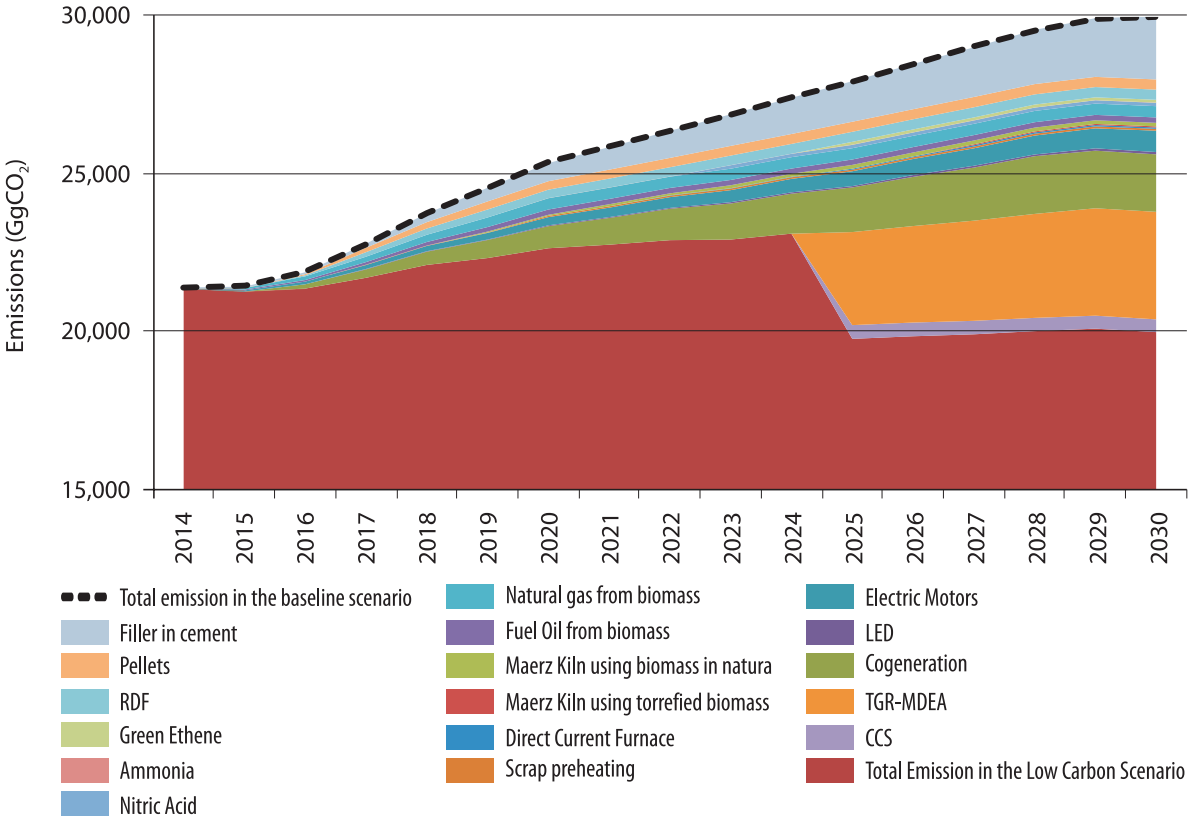
Table 28 – Low carbon measurements in the MACTool

Sector	Sub-sector	Measure
Chemical	Energy	Lighting with LED lamps
		NG cogeneration
		Implementation of more efficient motors
		Replacement of FO with firewood
		Replacement of NG with firewood
	Process	Recovery of purge gas in ammonia
		Catalytic conversion of nitric acid N_2O
		Bioethene production (ethene from ethanol)
Lime		Carbon Capture and Storage (CCS)
		Replacement of Azbe kilns with Maerz kiln using firewood in natura
		Replacement of Azbe kilns with Maerz kiln using torrefied firewood
Steel		TGRBF-MDEA
		Continuous feed and scrap preheating furnaces
		Direct current furnaces
Cement		Replacement of fossil fuel with RDF
		Replacement of fossil fuel with wood pellets
		Addition of filler in cement

Source: Prepared by the authors (2019) based on Fanti et al. (2017), Freitas, René Vogelaar and Renato Vogelaar (2017a, 2017b) and Punhagui et al. (2017).

17. The Incremental BECP differs from the simple BECP because the calculation is incremental (LCS minus BS). Since the MAC curve is also an incremental analysis, this is the BECP that allows compatibility between the curves.
18. Disregarding the potential avoided from the point of view of consumption. If this view is adopted, the emissions avoided by the cement and construction industries will account for 61.6% of the total (see appendix A)

Chart 34 – Wedge Graph for Sao Paulo's industry



Source: Prepared by the authors (2019) based on Fanti et al. (2017), Freitas, René Vogelaar and Renato Vogelaar (2017a, 2017b) and Punhagui et al. (2017).

In last place is the lime industry, with 4.8%. Regarding this result, it is necessary to consider the size of the industry and the consequent amount of emissions *vis-à-vis* the other sectors of Sao Paulo's industry analyzed in the study. In addition, this is the only sector that has a negative emission balance in the LCS with the shift of biomass to other sectors, achieved by the thermal efficiency of Maerz kilns. The idea of "negative emissions", mainly through the implementation of CCS together with the use of biomass is highly promising and should be the subject of future studies with extrapolation to larger production scales.

Starting in 2025, we will be able to see significant reductions in emissions from the steel industry, thanks to the TGRBF–MDEA technology, which is close to CCS, at least as regards the treatment of gases emitted during manufacturing processes. The TGRBF–MDEA accounts for 96% of mitigation in the steel industry. CCS itself implemented in the lime industry is quite representative from the point of view of total emissions from the industry, with 67%. In the chemical industry, the measure with the greatest potential is cogeneration through NG, with 53% of the sector's mitigation potential, especially because this measure presents substantially negative MAC and BECP, which makes it quite attractive to potential investors. In the cement sector, the measure related to filler insertion is the one with the greatest potential, accounting for 65% of total mitigation.

From the global standpoint, the mitigation potential of the analyzed period is 78.4 $MtCO_2e$. Therefore, avoided emissions between 2014 and 2030 account for about 18% of total emissions of the projected BS. Regardless of the evolution of

the industries' physical and economic production, in 2030 GHG emissions are 7% lower than in the first year of analysis, i.e., 2014. With the LCS technologies, in 2030 Sao Paulo's industrial sectors would succeed in reducing GHG emissions to 19.98 $MtCO_2e$/year, or 66% of the emissions projected for the same year in the BS.

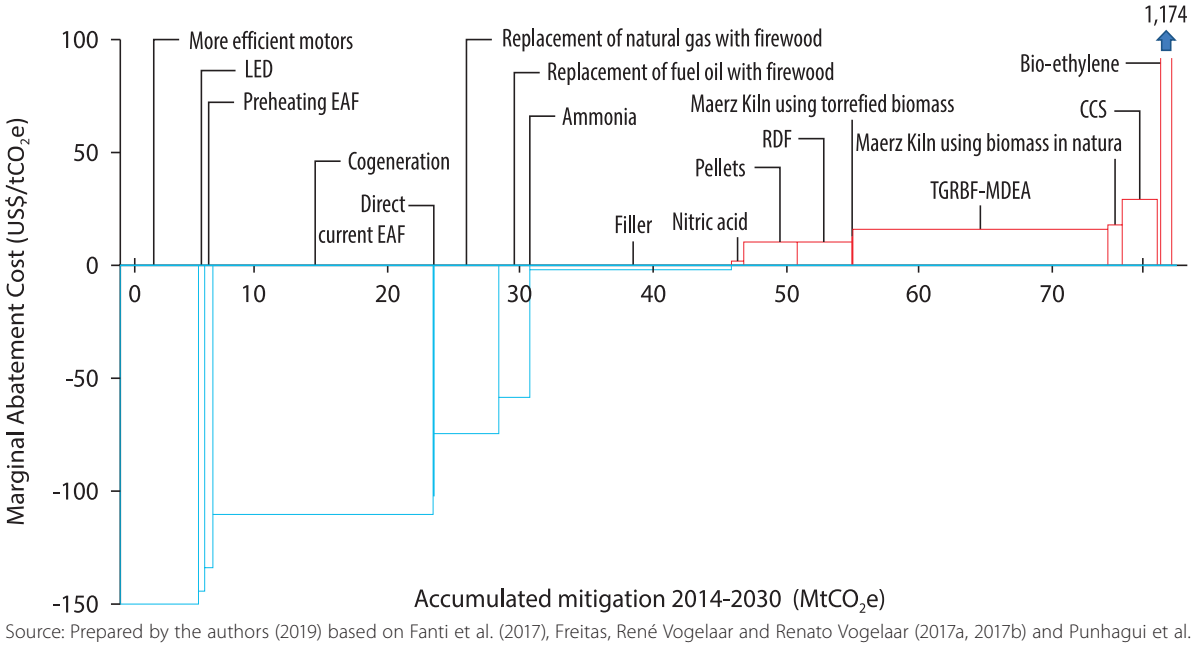
4.1.2 Marginal Abatement Cost Curve for the State of Sao Paulo

Chart 35 shows the MAC Curve with the 17 measures included in the Project. From left to right, the identification of the measures presented is shown from top to bottom, as seen in **Table 29**.

Table 29 shows the numerical values of MAC and GHG mitigation provided by each measure.

According to **Table 29**, there are 9 measures for which the economic result is negative. These measures are known as no regrets[19], that is, measures that have no cost to society and may even entail gains. Among these measures, the most attractive are those related to the energy sector, especially the ones involving the reduction of electricity consumption. The fourth lower MAC measure is cogeneration in the chemical sector, which is distinguished by electricity generation through the reduction of energy losses from natural gas combustion. The measure with the greatest reduction potential in the study, the TGRBF-MDEA measure, which is somewhat close to CCS from a technological standpoint but does not involve the stock of CO_2 in geological reservoirs, also has a considerably low MAC (less than USD 20 per mitigated ton). However, this measure depends on the

Chart 35 – Marginal Abatement Cost Curve for Sao Paulo's industry



Source: Prepared by the authors (2019) based on Fanti et al. (2017), Freitas, René Vogelaar and Renato Vogelaar (2017a, 2017b) and Punhagui et al. (2017).

19. "No Regrets" is a specialized literature term used to refer to GHG reduction measures whose benefits equal or exceed their costs to society, excluding the benefits of avoided climate change (IPCC, 2007).

Table 29 – Values of the marginal abatement cost curve for Sao Paulo's industry

Technology/low carbon measure	Marginal abatement cost	Reduction of emissions 2014–2030
	(USD/tCO_2e)	($MtCO_2e$)
Chemical: more efficient motors	–150	5.77
Chemical: LED	–145	0.57
Steel: preheating and continuous feed	–134	0.61
Chemical: Cogeneration	–111	16.46
Steel: direct current furnace	–102	0.27
Chemical: replacement of natural gas with reforestation wood	–75	4.79
Chemical: replacement of fuel oil with reforestation wood	–58	2.28
Chemical: ammonia	–27	0.06
Cement: filler	–2	15.14
Chemical: nitric acid	2	0.84
Cement: pellets	10	4.03
Cement: RDF	11	4.03
Lime: Maerz kiln using torrefied biomass	12	0.13
Steel: TGRBF-MDEA	16	19.27
Lime: Maerz kiln using biomass in natura	17	1.09
Lime: CCS	29	2.54
Chemical: Green ethylene	1,174	0.54

Source: Prepared by the authors (2017) based on Fanti et al. (2017), Freitas, René Vogelaar and Renato Vogelaar (2017a, 2017b) and Punhagui et al. (2017).

state's action to transport and inject CO_2 into its geological sink. It is also worth noting that in the measure with the third largest mitigation potential, namely filler addition, the economic result is virtually nil (USD -2/tCO_2). The emission reduction potential of this measure over the analysis period is 15 $MtCO_2e$.

If only negative MAC technologies — which prevail in the chemical and steel industries — were used, 45.95 $MtCO_2e$ would be avoided, with a savings of USD3.4 billion by 2030. If all 17 technologies were adopted to achieve the maximum potential of 78.4 $MtCO_2$, USD2.2 billion would still be saved by 2030.

4.1.3 Break-Even Carbon Price Curve

Chart 36 shows the BECP curve for the 17 measures included in the Project. From left to right, the identification of the measures presented in **Chart 36** is shown from top to bottom in **Table 30**.

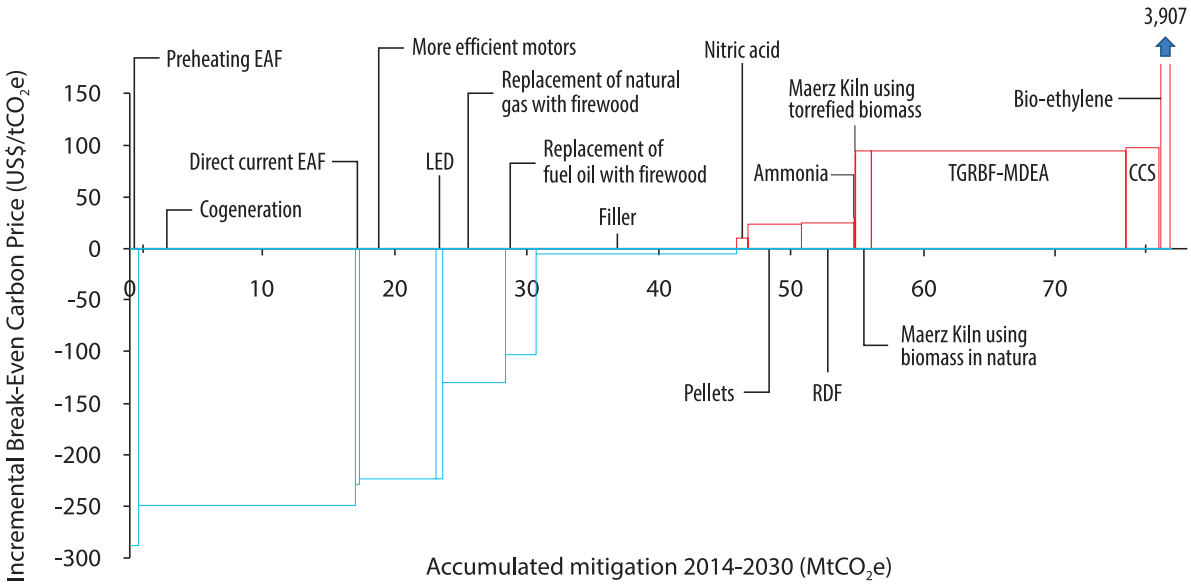
Table 30 presents the BECP values and GHG mitigation, which is the same as in Table 29, provided by each measure.

Although with the same emission mitigation potentials, the economic results of the BECP analysis are amplified in relation to MAC results. In general, the order of the measures does not vary greatly. Possible changes in the order of the measures are mainly due to the CAPEX representation in the cost composition of each measure. In the BECP calculation, the IRR Benchmark rate is the only variable that differs in relation to the MAC and acts on the levelization of the CAPEX, so that the larger the CAPEX in the total cost (which includes OPEX, energy cost and revenue) the higher the MAC increase for the BECP.

It is worth mentioning that cogeneration in the chemical industry, which has a considerable emission reduction potential, becomes the second most attractive option and with a very significant negative result (no regrets).

Altogether, 8 low-carbon technologies provide a return above that determined for the industry, and therefore are attractive investments. In the case of the other technologies, the ton of carbon needs to be sold for this to happen.

Chart 36 – Break-Even Carbon Price Curve for Sao Paulo's industry



Source: Prepared by the authors (2019) based on Fanti et al. (2017), Freitas, René Vogelaar and Renato Vogelaar (2017a, 2017b) and Punhagui et al. (2017).

Table 30 – Break-Even Carbon Price values for Sao Paulo's industry

Technology/low carbon measure	Incremental BECP	Reduction of emissions 2014–2030
	(USD/tCO_2e)	($MtCO_2e$)
Steel: preheating and continuous feed	– 288	0.61
Chemical: cogeneration	– 250	16.46
Steel: direct current furnace	– 229	0.27
Chemical: more efficient motors	– 224	5.77
Chemical: LED	– 224	0.57
Chemical: replacement of natural gas with reforestation wood	– 131	4.79
Chemical: replacement of fuel oil with reforestation wood	– 103	2.28
Cement: filler (SP)	– 5	15.14
Chemical: nitric acid	10	0.84
Cement: pellets (SP)	23	4.03
Cement: RDF (SP)	24	4.03
Chemical: ammonia	31	0.06
Lime: Maerz kiln using torrefied biomass	93	0.13
Lime: Maerz kiln using biomass in natura	94	1.09
Steel: TGRBF–MDEA	95	19.27
Lime: CCS	98	2.54
Chemical: green ethylene	3,907	0.54

Source: Prepared by the authors (2019) based on Fanti et al. (2017), Freitas, René Vogelaar and Renato Vogelaar (2017a, 2017b) and Punhagui et al. (2017).

4.1.4 Investment in low carbon measures

Chart 37 shows the investment intensity curve in the LCS. The intensity shows the investments needed per avoided tCO_2 compared to investments for the BS.

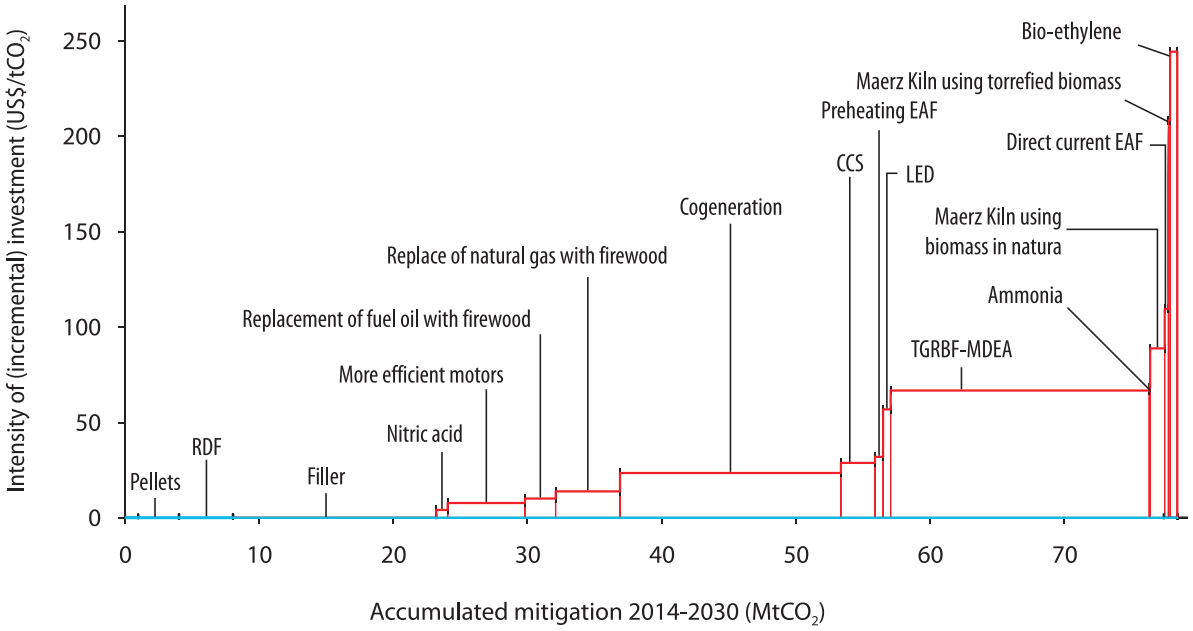
Table 31 shows the values used in the construction of the curve and adds the total (non-incremental) investment for each measure. The non-incremental investment corresponds to the investment for the LCS only, without considering the investment for the BS that might not occur.

As already mentioned in section 3.4.2, the measures to replace petroleum coke with biomass in the cement industry do not require any initial investments. On the other hand, the technology with the highest total investment (USD1,286 million by 2030) is TGRBF-MDEA, found in the steel industry.

However, it is seen that measures such as filler, TGRBF-MDEA and cogeneration can entail high total investments, but their investment intensity is relatively low since their mitigation potential, as already seen, is high. But the analysis of this measure considers that the state will be responsible for transporting CO_2 to the geological reservoirs in the case of TGRBF-MDEA and CCS technologies.

Another point of interest is that in the investment intensity curve, bioethene does not display a high value as seen in the MAC and BECP, although it continues to rank first in terms of cost. This reaffirms what has already been mentioned in section 3.3.3, i.e., that the price of ethanol, rather than the CAPEX of a new plant construction, is the major determinant of the total cost of bioethene.

Chart 37 – Intensity of (incremental) investment in low carbon measures for the State of Sao Paulo



Source: Prepared by the authors (2019) based on Fanti et al. (2017), Freitas, René Vogelaar and Renato Vogelaar (2017a, 2017b) and Punhagui et al. (2017).

Table 31 – Investment intensity and total cost of low carbon measures for the State of Sao Paulo

LCS technology/measure	Intensity of (non-incremental) investment	Total cost of investment
	(USD/tCO_2)	(USD million)
Cement: pellets (SP)	—	—
Cement: RDF (SP)	—	—
Cement: filler (SP)	0	701
Chemical: nitric acid	4	4
Chemical: more efficient motors	8	45
Chemical: replacement of fuel oil with reforestation wood	10	35
Chemical: replacement of natural gas with reforestation wood	14	100
Chemical: cogeneration	24	520
Lime: CCS	29	73
Steel: preheating and continuous feed	32	19
Chemical: LED	57	258
Steel: TGRBF-MDEA	67	1,286
Chemical: ammonia	68	4
Lime: Maerz kiln using biomass in natura	89	161
Steel: direct current furnace	110	721
Lime: Maerz kiln using torrefied biomass	208	43
Chemical: green ethene	244	370

Source: Prepared by the authors (2019) based on Fanti et al. (2017), Freitas, René Vogelaar and Renato Vogelaar (2017a, 2017b) and Punhagui et al. (2017).

4.2 DISCUSSIONS

The measures analyzed in the present study showed various MAC, BECP and mitigation potentials. Going beyond costs and emissions, each measure has peculiarities of different types, such as technical and regulatory.

In comparison with previous studies, which generally link the future to a single macroeconomic scenario, in this study the evolution scenarios of the industries' physical production are distinct and characterized according to the perspectives of the experts from each sector.

An important result is the use of RDF as an alternative fuel in the cement industry. This technology has the potential to reduce 4 $MtCO_2$, which is quite significant. It is an interesting measure that is already being implemented in other Brazilian states and, therefore, its viability in the State of Sao Paulo depends on adjustments to the state's regulatory framework.

For industries such as the chemical industry, in which energy consumption stands out, the mitigation potential of measures based on the reduction of energy consumption is significant. Cogeneration has the potential to mitigate 16.5 $MtCO_2$. However, the investment intensity for this type of project is USD 24/tCO_2, which can be a barrier for this technology to be massively adopted. In addition, caveats to this result should be made, because in this case and in some others (see Table 2), the EF of the CDM was considered to estimate emissions. In this case, the role of the state as facilitator proves indispensable.

Although the CDM EF is a legitimate approach, it depends on political support to be validated. The CDM assumes that the electricity sector avoids the increase in supply by more carbon-intensive sources, in which measures to reduce electricity consumption or its generation through renewable sources or cogeneration exist. However, the EF inventory had to be adopted for some of the measures, since the Brazilian interconnected system has several types of plants, not only the highest emitting ones. On the contrary, the share of hydroelectricity is still significant. Besides, there are technologies that consume more electricity in the LCS than in the BS. In this case, the emission factor for inventories was used.

It is also worth mentioning that thanks to the alternatives studied in the project, the reduction of CO_2 emissions through electricity savings will become increasingly relevant. This is because, according to the scenarios pointed

out in several studies, the increase in global temperature will cause water deficits that will compromise the supply of energy by hydroelectric plants, thus increasing the share of fossil sources, which are not only "dirtier" for the environment but also raise the price of electricity. Add to that the greater difficulties for hydroelectric development due to its high environmental and financial costs.

From the standpoint of energy sources, the options with the highest MAC are related to energy vectors from biomass. Thus, the analysis of mitigation measures related to energy consumption by the industry and to the energy sector requires dynamic tools that integrate the evolution of the energy matrix and can identify the shifting potential of fossil sources throughout the analyzed period, considering also the economic result of the technologies. The use of these tools is relevant to avoid double counting while identifying the existing maximum mitigation potential.

Finally, it is worth considering more aggressive measures, which in a way are already recommended by the market of the industrial products from the analyzed sectors. The lime sector is experiencing a retraction and is substituting lime for other substances. This dematerialization could be considered in a more aggressive fashion. Likewise, the estimate that the shutdown of the only blast furnace in the integrated steel production route in the state implies a reduction of about 104 million tCO_2 by 2030, could also be considered as an opportunity for a radical change in the state's steel industry. That is, the recovery of steel production in the future could be based on a plant with state of the art low carbon technology. This potential is more than five times greater than that of the measure with the highest emission reduction potential (TGRBF-MDEA itself) and integrates the MACTool proposed in this report.

Another point of discussion are the comparisons that can be made between the results of this study for Sao Paulo and the study carried out for Brazil in 2010. The BS projected for Brazil in the year 2030 is 1,718 $MtCO_2$ (GOUVELLO et al., 2010, 31). Excluding the 31% related to deforestation, since it has a negligible weight in the case of Sao Paulo, we have the emission of 1,185 $MtCO_2$, while the value found for Sao Paulo's industry was 30 $MtCO_2$ in the same year. The total mitigation accumulated over the period (2008-2030) in the study for Brazil was 11.1 $GtCO_2$, in other words, 483 $MtCO_2$ per year. Compared to this figure, the annual average of avoided emissions for Sao Paulo's industry, which is of 4.6 $MtCO_2$, represents 0.96%.

Disregarding the measures that present a considerable deviation in the MAC Curve for Brazil (Sao Paulo-Rio bullet train) and in the MAC Curve for Sao Paulo (bioethene), for Brazil there were values of USD/tCO_2 in a range from –120 to 106[20] (Gouvello et al., 2010, pp. 157 and 158). In turn, this study presented a range from –150 to 29. This indicates that there are greater opportunities to generate savings through low carbon development in the state when compared to Brazil. Another fact is that, as in the case of Sao Paulo, the measures with a negative MAC in the study for Brazil are mostly in the area of energy efficiency. This reinforces what has been mentioned several times throughout this report about the savings linked to GHG mitigation through energy efficiency.

20. Considering the 8% discount rate, which is the same used on the study. However, the World Bank study also presents results for 4% and 12%.

4.3 UNCERTAINTIES AND RECOMMENDATIONS

Equally relevant to the presentation of the results are the limitations and difficulties faced throughout the execution of this project. One of the main goals of the study was to identify possible directions for a low carbon future, with a specific focus, namely Sao Paulo's industrial sector. Once decision-makers opt for certain paths, further studies should be carried out to widen the scope and expand the technical, political, regulatory, social, and environmental character of these low-carbon technologies. The following are some of the difficulties to be considered in future analyzes.

The values for the initial period (base year 2013) were established at a time when the economy displayed significant and distinct characteristics in relation to the years following the study, which made up the initial projection years (2014, 2015 and 2016). In a scenario where the economy behaved differently over a short time span, the projections may not correspond to the possibilities presented, since rather than making forecasts the study presents a development pathway for a possible future based on a specific point in time. Considering the scenario of volatility and uncertainties, the economy may either recover to close to the initial levels used as a baseline in the near future, or take longer to do so. These macroeconomic issues that permeate the context and may impact the final results of this study were beyond the scope of this project.

An example is the price of Brent oil — which served as the basis for the prices of other forms of energy addressed in this study — which was close to USD100/BOE in 2013 and projections indicated that it would remain on average at USD110/BOE (EIA, 2014a). However, the current data for 2017, for example, did not exceed USD60/BOE.

Regarding data collection, the main challenge was to obtain data that were representative of the industry, since in general companies link their established privacy and market policies to commercial strategies.

For the estimates, the costs of the technologies were kept constant throughout the study period, disregarding inflation and obsolescence, that is, in general, technological advances impact on the prices of technologies, thus reflecting their consolidation or substitution for more advanced technologies that at the time are in an experimental stage.

The price of firewood used in the study was taken from CEPEA/ESALQ and represents a state average. For other fuels, except for charcoal, national averages were used, based on the time series of the National Energy Balance (BEN). The price of ethanol was linked by the model to oil prices, which may not clearly reflect the price evolution in the Brazilian market, since fuel prices in Brazil are strictly controlled by the federal government and different tax rates apply to different fuels.

The technologies used in the study consider information on costs and emissions found in the literature, in accordance with the experts' analysis. For some technologies, as is the case of the energy sector in the chemical industry, average data already processed in other studies were used to establish use and cost assumptions. As for the other industries covered, the data were obtained directly from the companies representing each industry and technology and from specific studies that, in large part, provided information in an international context in relation to application and costs.

In some technologies, implementation in terms of costs and emissions was simplified. For example, in incremental technologies, the cost of adapting existing technological structures was not considered in some cases. In other cases, when it was not possible to obtain the price

of a given technology, the costs of the technology of interest were established by comparison with another technology deemed similar by the authors. In the case of TGRBF-MDEA, the cost of the final disposal of CO_2 was not considered.

Some of the technologies considered in the sectors were shaped after the international context, disregarding possible import taxes, since many of them have not been developed and consolidated in the country.

Seeking to obtain an integrated analysis, the study was developed in such a way as to avoid possible double counts between the technologies used. In the study for the cement industry, for example, the analysis was performed in such a way that internal changes in the application of a measure led to impacts on the other measures and, consequently, on the entire study. Interactions were also observed between sectors, as in the case of the steel and cement industries, due to the interrupted supply of slag resulting from the shutdown of USIMINAS. However, the analysis did not include an integrated top-down model that presented, for example, the evolution of all energy vectors over the period of analysis.

Considering the use of the MACTool, strategies were used to overcome its limitation, by adapting the MACTool programming according to needs.

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 pointed out that this study 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.

5 Final considerations

The exploratory study allowed quantitative assessments of emissions and costs as a result of the 17 options evaluated and, therefore, it can provide a basis for decision-making and its implications. The study addressed the mitigation potential of actions related to energy efficiency, both thermal and electrical; the replacement of fossil fuels with renewables; and, finally, the introduction of aggressive capture measures such as CCS and TGRBF-MDEA. In addition to the relevance of the results, the study provides a database that can be used and complemented in the future, and is stored in an electronic spreadsheet. This is an unprecedented study that can guide the low-carbon development of Sao Paulo's industrial sectors.

Among the 17 measures analyzed, 9 have a negative cost, that is, the adoption of these measures to the detriment of the projected BS would be beneficial. All 17 measures for the four sectors assessed would have the potential to mitigate 78.4 million tons of CO_2 by the year 2030. The average MAC result, weighted by the mitigation potential, indicates a negative value of USD 29.15/TCO_2.

From the standpoint of the reduction targets set by the PEMC, the results of the study show that there are several possibilities for achieving them and that the economic context and the market can facilitate the reduction of emissions through no regret of even spontaneous measures. However, certainly the presence of the state through regulations is necessary for the measures to last and be efficiently and fairly allocated.

According to the publication *Decarbonizing Development: Three Steps to a Zero-Carbon Future* (FAY, 2015), planning for a low-carbon future depends on up-front actions for this goal to be achieved, and all means for implementing these actions should be in agreement as regards the need for decarbonation in the activities of all economic sectors.

Efforts do not need to follow the same direction and speed, but fewer efforts at the beginning may require greater efforts in the future. On the other hand, higher initial investments can generate returns over the years, which are equal to or even higher than these investments, as shown in the study. In this context, the assessment of carbon prices (MAC and BECP) can guarantee that cheaper reduction options will be adopted and that organizations will equalize marginal costs to ensure the necessary conditions for an efficient transition. However, we must not forget that the MAC Curve is dated to a reference year and a specific period and that the climate issue is a long-term problem. In this sense, the results of this study are a seminal point for the discussion of mitigation possibilities for Sao Paulo's industry.

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6

Appendix A

Low carbon study for Sao Paulo's industry including construction

INDIRECT EMISSIONS FROM WORLDWIDE MATERIAL CONSUMPTION

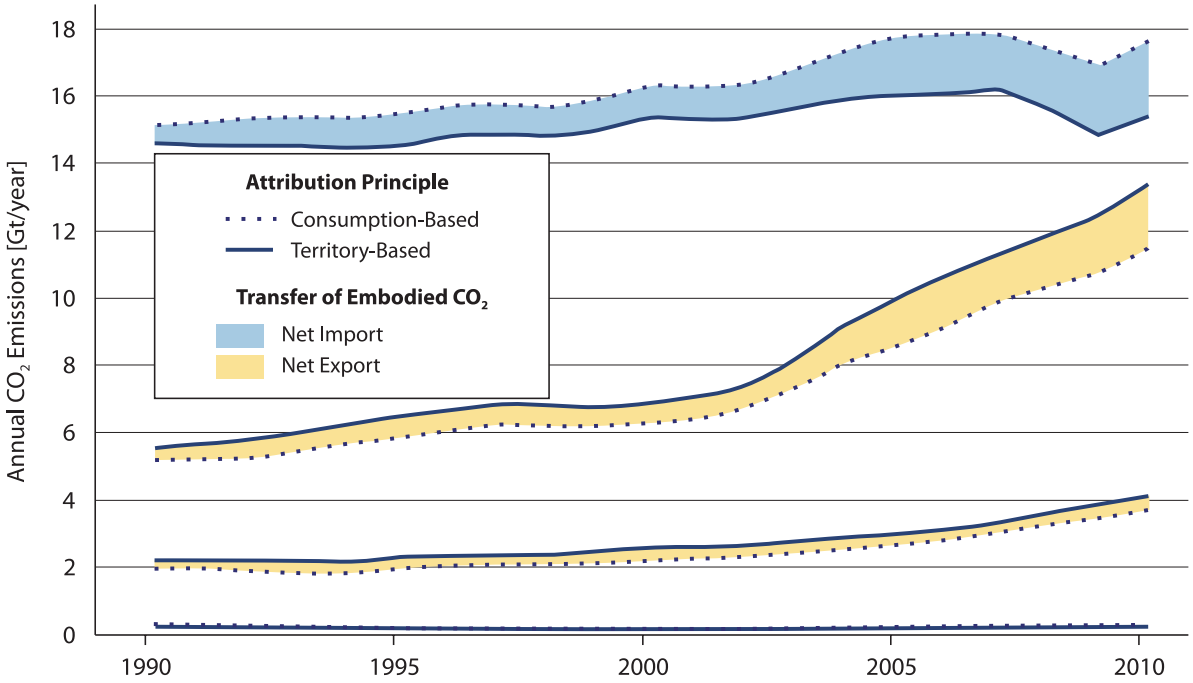
One of the approaches presented by the IPCC report (VICTOR et al., 2014) is the accounting of emissions from the viewpoint of consumption, where it can be seen that, in fact, many high-income countries are importing emissions embodied in products, mainly from upper-middle income countries (**Figure 10**).

Figure 10 shows CO_2 emissions from fossil fuel burning for four economic groups attributed according to territory (solid line) and final consumption (dotted line). The shaded areas are the net balance of CO_2 trading between each of the groups and the rest of the world. Blue indicates that the region is a net importer of emissions, with per capita CO_2 emissions from consumption higher than those occurring in its territory. Yellow indicates the opposite situation, i.e. exporters of emissions embodied in goods. Low-income countries, which have no great relevance in the global trade of manufactured goods, show no difference between emissions by territory and consumption. For upper-middle income countries, in turn, per capita emissions embodied in exported goods have grown over time.

The comparison of emissions from consumption and production shows considerable variations with respect to the relevance of and responsibility for the countries' emissions, as seen in **Figure 11**. For the sake of illustration, a ton of steel produced in China but exported to the United States results in emissions in China, although the fundamentals of demand for steel originated in the United States. **Figure 11** shows the estimated emissions from consumption and production in 2010, ranked up to 75% of global emissions. The approach on the demand side is an alternative way for holding countries accountable for GHG emissions.

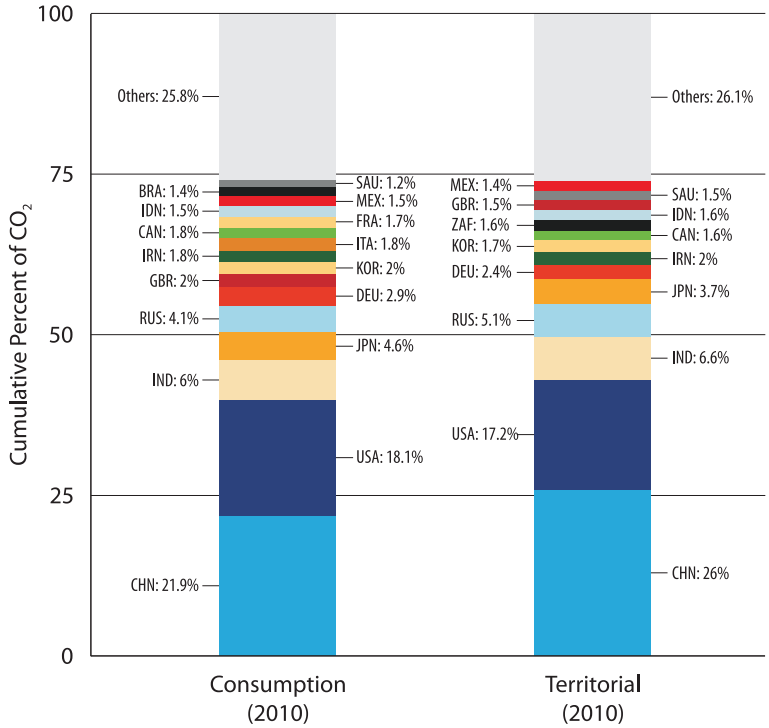
In **Figure 11**, the left and right bars show the ranking of countries based on consumption and territory, respectively, considering emissions

Figure 10 – Emissions based on economic sector, territory and consumption



Source: Victor et al. (2014).
Note: HIC (high-income countries), UMC (upper-middle-income countries), LMC (lower-middle-income countries) and LIC (low-income countries).

Figure 11 – Ranking of emissions by country, consumption and territory considering fossil fuel burning



Source: Victor et al. (2014).

from fossil fuel burning. There are considerable variations for China and the United States, for example. Although in the general ranking not many differences are observed when these trade effects are included, in absolute terms the difference is relevant.

From the territorial perspective, China emits 3.9 $GtCO_2$/year and from the consumption perspective, 3.8 Gt/year. Considering consumption, the U.S. emits 3.2 $GtCO_2$/year and the territory emits about 2.6 $GtCO_2$/year, representing 24% less than the consumption-based approach. From the consumption perspective, China's emissions are 0.6 $GtCO_2$/year higher than those of the U.S., accounting for 19.4%. From the territorial perspective, China's emissions are 1.4 $GtCO_2$ higher than those of the U.S., with 53.6 $GtCO_2$.

Figure 11 shows that from the consumption perspective, Brazil accounts for 1.4% of global emissions, but in relation to the territorial approach this figure is negligible.

Figure 11 also shows that, in terms of responsibility for consumption, 4 countries alone account for more than half of the emissions. This perspective suggests that while all countries have important roles to play in reducing emissions, the overall impact of mitigation efforts should be concentrated in a few countries. Thus, it is possible that measures and technologies aimed at streamlining consumption could play a relevant role in mitigating emissions.

This global scenario presented by the IPCC is one of the main reasons why this section of the present study uses the consumption perspective. Construction, although not classified as an industrial sector, uses large amounts of materials from other industries such as cement and steel. New structural arrangements can reduce the amount of material used while maintaining the required quality and safety standards.

INDIRECT EMISSIONS FROM THE CONSUMPTION OF MATERIALS IN SAO PAULO'S CONSTRUCTION INDUSTRY

Energy conservation measures reduce GHG emissions to the extent that more efficient technologies prevent energy consumption. Thus, a similar idea can be applied to the consumption of materials. Specifically, this study assesses the construction industry, in which emissions are considered from the perspective of consumption, which differs from the other industries covered, in which the production perspective was considered.

The results of the study are presented here from the consumption perspective, including the demand for cement by the construction industry in the State of Sao Paulo. The study presents the basic concepts involving indirect emissions from the consumption of materials, dematerialization and the position of the construction industry as an important sphere that intersects with the other sectors addressed. The scenarios for cement consumption, energy consumption and the resulting GHG emissions, as well as the costs associated with the three new low carbon measures proposed for the construction industry are also discussed. Finally, the study presents the results of the Wedge Graph, the MAC Curve and the BECP curve considering all the twenty measures assessed.

The inclusion of mitigation measures from the perspective of material consumption (cement industry including construction) is an innovative proposal from the standpoint of political possibilities to mitigate emissions and of the responsibility for said emissions. It is the search for measures that seek to streamline the use of industrial inputs to meet the demands of society while mitigating GHG emissions. To be feasible, these measures require an appropriate regulatory environment, and certainly the search for this condition will spark debates about responsibility for global GHG emissions.

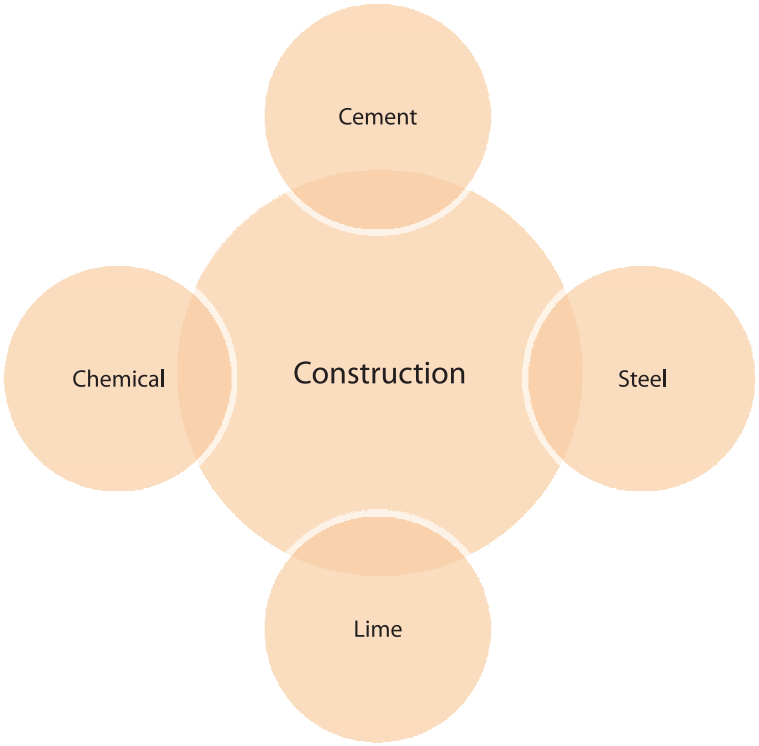
Although it involves companies from different sectors, the decrease in consumption of cement and lime for mortar and of cement and steel for reinforced concrete implies reducing emissions from the industries that manufacture these inputs. That is, the companies involved in construction projects, although not directly related to the sources of emission of the inputs are deemed responsible from the consumption perspective. The relationship between the construction activity and the industrial sectors assessed in this project can be seen in **Figure 12**. Part of the emissions from these sectors can be reduced by streamlining their products that are used by the construction industry.

In conclusion, the consumption approach considers indirect emissions from both process and energy, embodied in the manufacture of the materials to be consumed. In this study, we use this approach for emissions related to cement consumption by the construction industry.

In Brazil, the cement industry already benefits from a clean energy matrix and uses efficient production technologies, which results in low emission levels when compared to other countries. In this regard, GHG mitigation measures, which focus only on cement production in the state, do not yield meaningful effects. Therefore, Project BR-T1262 sought to include the construction industry in the analysis integrated to the cement sector from the perspective of material consumption, as already mentioned.

As will be presented in subsequent sections, the mitigation potential resulting from the replacement of clinker with filler is huge. The increased share of concrete and mortar manufacturing also has a great mitigation potential, as it avoids cement waste and increases "$t_{concrete}/t_{cement}$" and "t_{mortar}/t_{cement}" efficiency. These measures alone, out of all 20 measures in the Project, represent 42.1% of the total emissions avoided by Sao Paulo's industry.

Figure 12 – Interrelation between the construction industry (consumer) and other industries (producers)



Source: Prepared by the authors (2017)

COMPARISON BETWEEN CEMENT PRODUCTION AND CONSUMPTION IN THE STATE OF SAO PAULO

The projection of cement consumption was based on increased concrete and mortar consumption, since cement is used in the manufacture of these products. The same 5% p.a. rate was used for the increase in concrete and mortar consumption. The study also considered the increased share of concrete and industrial mortar, which is an important assumption, since the specific consumption of cement (in kg/m^3) varies if these products are prepared on site as opposed to factory-made. Therefore, an 8% increase in the amount of industrial concrete by 2030 was adopted, with industrial mortar accounting for 80% of the market share[21] in the same year (PUNHAGUI et al., 2017).

Data on cement production (integrated route and milling) and consumption in the state is shown in **Table 32**. It can be seen that, because consumption is 66% higher than production, Sao Paulo imports cement from other states to meet its demand.

Chart 38 shows cement production and consumption in the state from 2014 to 2030.

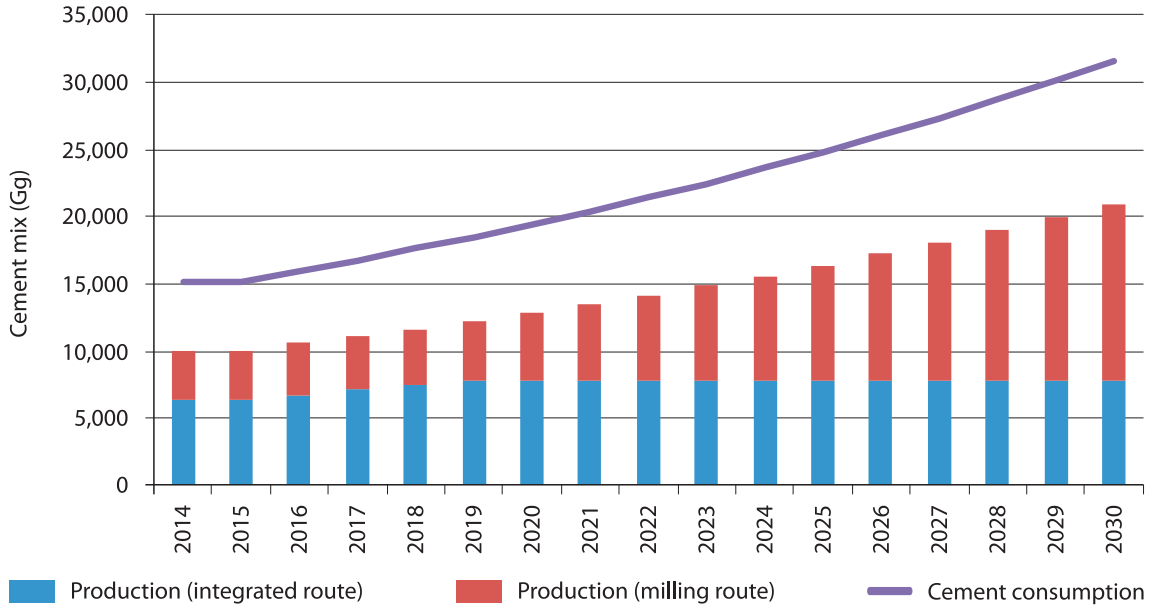
21. Market share is the level of participation of a company in the market in terms of sales of a specific product.

Table 32 – Projected cement production and consumption in the State of Sao Paulo

Year	Cement production (integrated route)	Cement production (milling)	Cement consumption
	(Gg)		
2014	6,413	3,607	15,155
2015	6,441	3,623	15,221
2016	6,763	3,804	15,982
2017	7,101	3,995	16,781
2018	7,457	4,194	17,620
2019	7,800	4,433	18,501
2020	7,800	5,045	19,426
2021	7,800	5,687	20,397
2022	7,800	6,361	21,417
2023	7,800	7,069	22,488
2024	7,800	7,813	23,613
2025	7,800	8,593	24,793
2026	7,800	9,413	26,033
2027	7,800	10,274	27,334
2028	7,800	11,178	28,701
2029	7,800	12,126	30,136
2030	7,800	13,123	31,643

Source: Prepared by the authors (2017) based on Punhagui et al. (2017)

Chart 38 – Projected cement production and consumption in the State of Sao Paulo



Source: Prepared by the authors (2017) from values on Table 25.

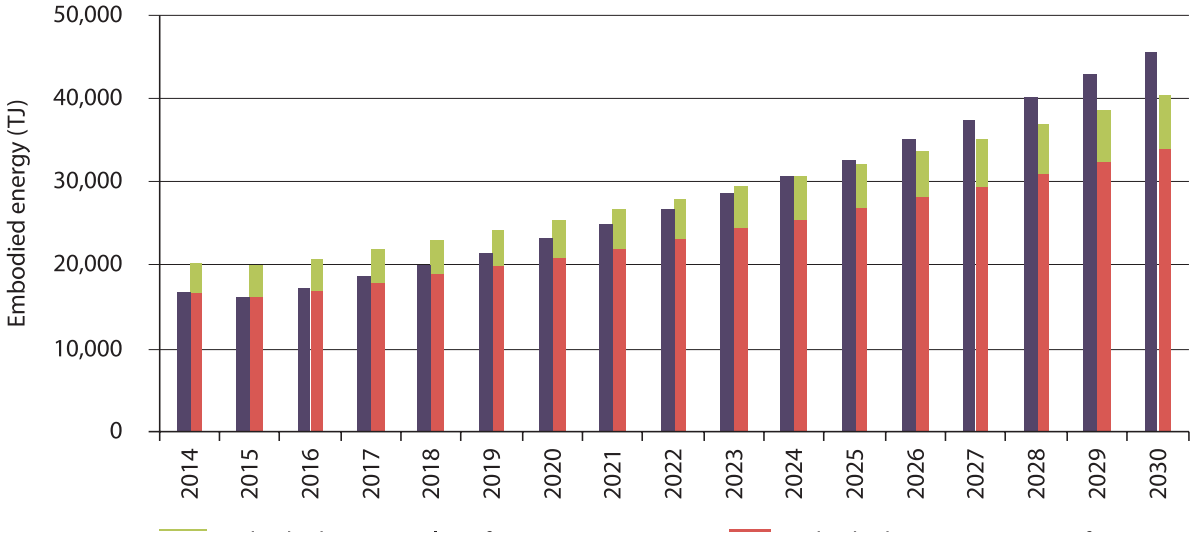
ENERGY CONSUMPTION

From the consumption perspective, **Chart 39** shows the energy embodied in the total consumption of cement intended for concrete and mortar until 2030. It should be noted that in the case of mortar, part of the energy is embodied in the lime manufacturing process.

CO2 EMISSIONS

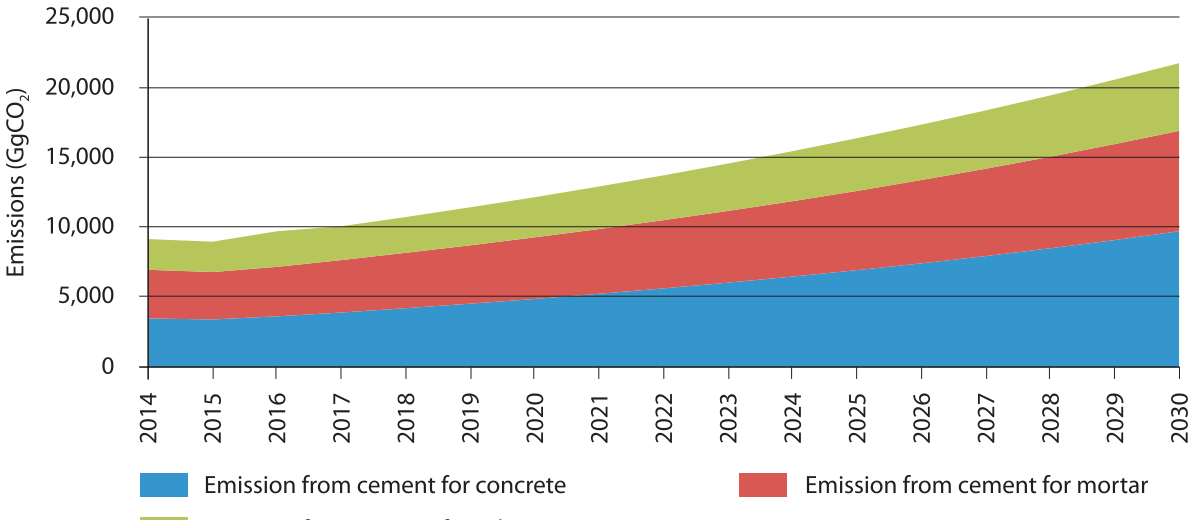
Chart 40 shows the evolution of total cement emissions from the consumption perspective. It is possible to see the share of cement for concrete (42%), cement for mortar (35%) and cement for other uses (23%) in total emissions in 2030.

Chart 39 – Projected consumption of energy embodied in the cement consumed in the State of Sao Paulo



Source: Prepared by the authors (2017) based on Punhagui et al. (2017)

Chart 40 – Total emission from cement consumption in the State of Sao Paulo broken down by consumption of concrete, mortar and cement for other uses



Source: Punhagui et al. (2017)

COMPARISON OF EMISSIONS OCCURRING INSIDE AND OUTSIDE THE STATE OF SAO PAULO IN THE BASELINE SCENARIO

Considering the boundaries of the State of Sao Paulo, emissions from cement production would be limited only to emissions from both processes and the energy consumed within its territorial limits (excluding clinker production in other states). On the other hand, cement emissions from the consumption perspective include emissions from both processes and the energy consumed in the activities carried out within and outside the state's geographical boundaries. Considering these two cases in the BS, **Table 33** shows that indirect emissions from consumption are almost two times greater than those occurring in SP in the year 2030. In 2014 this difference was 4,973 $GgCO_2e$ and in 2030, 15,637 $GgCO_2e$. In the period under analysis, indirect emissions from cement consumption in the State of Sao Paulo would total 152,498 $GgCO_2e$.

One of the approaches presented by the IPCC report (VICTOR, D.G et al., 2014) is the accounting of emissions from the consumption perspective and considering production in the territory, which clearly shows the difference between these approaches.

In the survey of emissions from cement production in Sao Paulo, either all process emissions or only those from the State of Sao Paulo can be considered. In the latter case, only emissions from clinker produced in the state (emissions in the sixth column in **Table 33**) would be considered. These emissions do not include limestone decarbonation and the

Table 33 – Emissions from cement production vs. emission from cement consumption in Sao Paulo

Year	Cement consumption (SP)	Total cement production (SP)	CO_2 emission from consumption (SP)	CO_2 emission from total production (SP)	CO_2 emission from production (SP) (1)	Difference (2)
	(Gg)		($GgCO_2e$)			
2014	15,155	10,020	8,731	5,773	3,758	4,973
2015	15,221	10,064	8,537	5,645	3,676	4,861
2016	15,982	10,567	8,997	5,949	3,874	5,123
2017	16,781	11,096	9,610	6,354	4,137	5,473
2018	17,620	11,651	10,253	6,779	4,413	5,841
2019	18,501	12,233	10,929	7,226	4,702	6,226
2020	19,426	12,845	11,638	7,695	4,746	6,892
2021	20,397	13,487	12,383	8,187	4,817	7,565
2022	21,417	14,161	13,165	8,705	4,886	8,278
2023	22,488	14,869	13,986	9,247	4,953	9,032
2024	23,613	15,613	14,848	9,817	5,018	9,830
2025	24,793	16,393	15,753	10,416	5,080	10,673
2026	26,033	17,213	16,703	11,044	5,141	11,563
2027	27,334	18,074	17,701	11,704	5,200	12,502
2028	28,701	18,978	18,749	12,397	5,257	13,492
2029	30,136	19,926	19,850	13,125	5,313	14,537
2030	31,643	20,923	21,005	13,889	5,367	15,637

Source: Prepared by the authors (2017) based on Punhagui et al. (2017)
(1) Considering only emissions by the integrated route and the electricity consumed in milling in the State of Sao Paulo.
(2) Difference between total emissions from consumption (column 4) and territorial emission (column 6).

burning of fossil fuels for clinker production in other states. However, demand by the state causes off-site emissions, since clinker is produced to meet its needs and it is currently not possible to build new integrated plants (with kilns for clinker production).

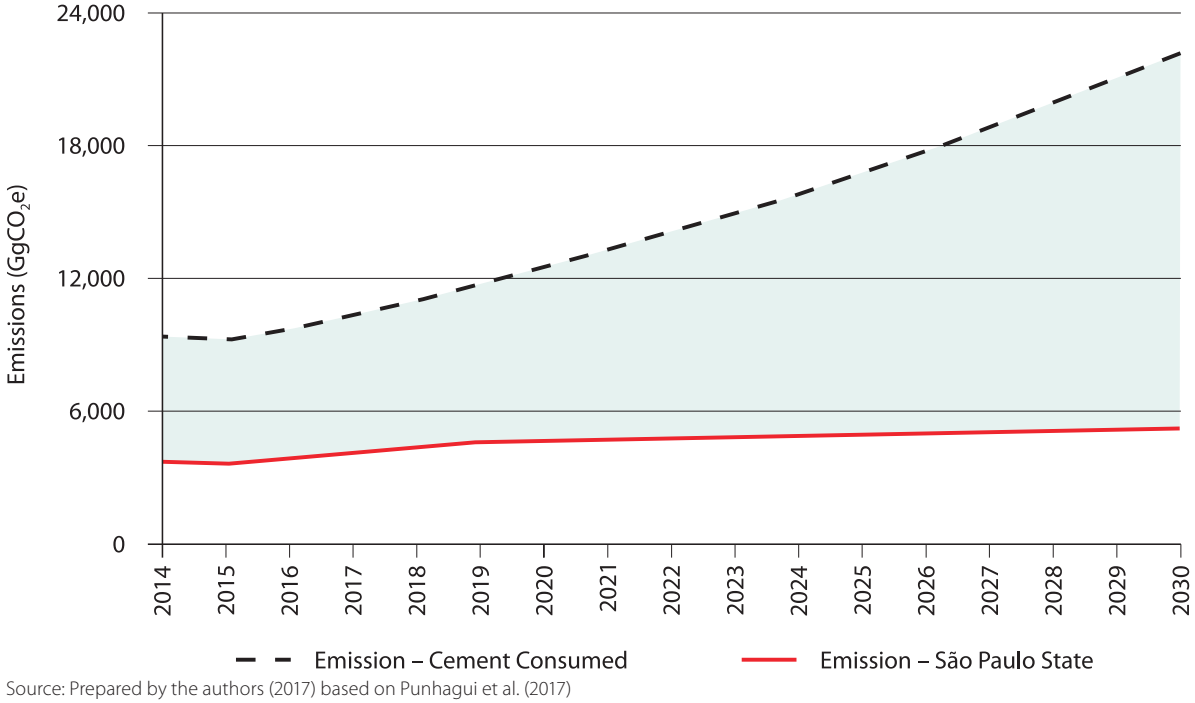
As cement production in Sao Paulo is insufficient to meet the state's demand, part of the cement consumed is fully produced in other states. Thus, CO_2 emissions from cement consumption in Sao Paulo cover all process and energy consumption emissions from the production of this cement, including where production occurs outside the state's geographical limits. The data presented in the last column of Table 33 refer to indirect emissions caused by the difference between cement consumption in Sao Paulo and cement produced via the integrated route in the state.

Chart 41 was prepared from data in Table 33, showing emissions from the consumption perspective and from production in the State of Sao Paulo, excluding emissions from clinker produced in other States.

LOW CARBON SCENARIO IN THE CONSTRUCTION INDUSTRY

The basis of the LCS in the construction industry lies in the process of dematerializing the use of cement in concrete and mortar production. Three measures were assessed using dematerialization: (i) increased use of ready-mixed (industrial) concrete to the detriment of concrete prepared on site; (ii) introduction of mixers for concrete production; and (iii) increased use of industrialized mortar to the detriment of mortar prepared on site.

Chart 41 – Greenhouse gas emissions in the State of Sao Paulo: SP Production (excluding emissions from clinker production in other States) vs. Consumption



Source: Prepared by the authors (2017) based on Punhagui et al. (2017)

Dematerialization

Allwood et al. (2011) highlight the importance of material consumption in GHG generation. Global demand for materials such as cement, steel, paper and aluminum has quadrupled in the past 50 years and contributed to the increase in emissions.

There are several instruments to promote dematerialization, from technical instruments such as information, research and development and certifications to instruments of a political nature such as taxes, subsidies and incentives (ALLWOOD et al., 2011).

Consequently, material efficiency can become as profitable as energy efficiency. Further studies are still needed in this area to address unsolved issues and overcome the economic, legal, regulatory, and social barriers that exist in the current (domestic and global) scenarios.

READY-MIX CONCRETE

When concrete prepared on-site is replaced with ready-mix concrete, there is a material savings in cement consumption in terms of kilograms of cement per cubic meter of concrete. By applying this measure, consumption of cement for concrete is reduced by 20%, which proportionally decreases related CO_2 emissions (PUNHAGUI et al., 2017).

The price of one ton of ready-mix cement used in the BS is USD170.62. Ready-mix concrete is sold ready to use and its price is set in USD/m^3. The expert arrived at an average price per cubic meter with the sector companies of USD129.63, but this price was disregarded throughout the analysis (PUNHAGUI et al., 2017).

READY-MIX CONCRETE PLUS MIXER

This measure is additional to the previous measure. When the mixer is used together with ready-mix concrete, the reduction in consumption of cement for concrete increases to 29%, to which the mixer contributes 9% (PUNHAGUI et al., 2017).

The cost of a concrete mixer was assessed at almost USD92,600, and the total cost of a concrete plant with mixer (infrastructure, wheel loaders, trucks) was estimated at USD2.28 million.

INDUSTRIALIZED MORTAR

Following the same logic as in the ready-mix concrete measure, industrialized mortar leads to a reduction of 11.5% in cement consumption (PUNHAGUI et al., 2017).

The price of one ton of ready-mix cement used in the BS is USD170.62, whereas the price of one ton of industrialized mortar was estimated at USD55.95 (PUNHAGUI et al., 2017).

BARRIERS TO THE LOW CARBON SCENARIO IN THE CONSTRUCTION INDUSTRY

The following are possible barriers to the LCS in the construction industry (PUNHAGUI et al., 2017):

Low profitability of companies that operate in the formal market and compete unequally in a heterogeneous market — in which different levels of informality exist — with companies that do not pay taxes and use aggregates of suppliers that do not have an environmental license. Profitability improves for ready-mix concrete companies when real estate income can be exploited; High level of competitiveness due to the inexistence of great technological differentials that contribute to the distinction of products. Most

companies operate with the same techniques, materials and equipment for production, which does not present great differences in terms of dosage between ready-mix concrete and concrete mixed on site;

There are no significant investments in the sector. Concrete mixed on site does not require investment in trucks, silos and production support elements like laboratories, engineers, technicians and drivers among others;

Ready-mix concrete companies usually mix the concrete in mixer trucks, sparing the use of mixers in the production plant, which could improve cement consumption and final product performance due to increased control. The use of mixers is avoided due to the Value-Added Tax on Sales and Services (ICMS);

Unlike concrete mixed on site, ready-mix concrete is subject to Service Tax (ISS), which varies between 3% and 5% in the State of Sao Paulo;

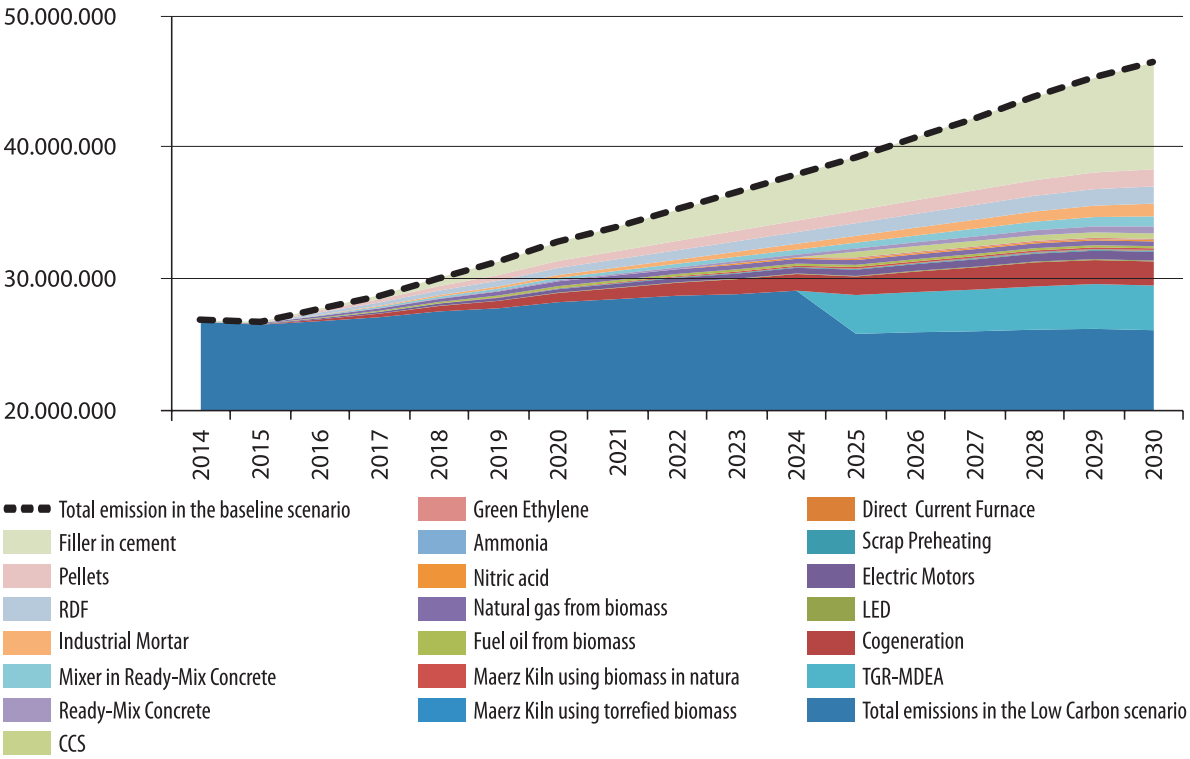
Transportation is another factor that increases the cost of ready-mix concrete, which is affected by traffic conditions and distances, mainly in the city of Sao Paulo;

Industrialized mortar faces difficulties in market competition with mortar mixed on site due to the failure to compare volume gains from its use (increase of about 20% for the same quantity of cement), which affects construction costs; The competitiveness of industrialized products also suffers from the lack of comparison in the loss of inputs.

EMISSIONS AVOIDED BY LOW CARBON TECHNOLOGIES INCLUDING THE CONSTRUCTION INDUSTRY

Chart 42 shows the emissions avoided by the 20 strategies in the LCS, which includes emissions and mitigation that occur outside the borders of Sao Paulo.

Chart 42 – Wedge Graph for Sao Paulo's industry including construction



Source: Prepared by the authors (2017)

The analysis enables concluding that it is possible to reduce almost 144 $MtCO_2e$ from 2014 to 2030. This is 83% more than mitigation, considering the territorial limits of Sao Paulo alone. This approach therefore increases the possibilities for reducing CO_2 emissions, which in fact extend beyond territorial borders.

From the consumption perspective, three new measures in the construction industry are included, which contribute to the mitigation of GHG, with 15 $MtCO_2e$ avoided. This inclusion, when the possibility of increasing the filler content in all the cement consumed by the state is considered, more than triples its reduction potential in relation to what would occur in the case of cement production alone. Filler becomes the measure with the highest potential analyzed in the study, with 50.3 $MtCO_2$ (35% of the emissions avoided over the period).

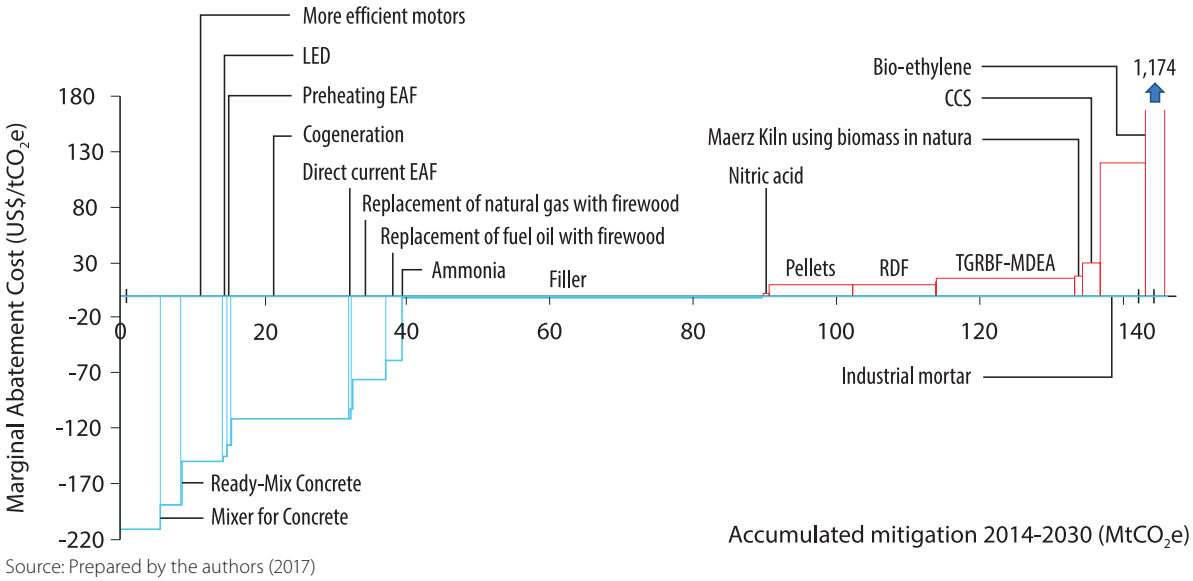
MARGINAL ABATEMENT COST CURVE INCLUDING THE MITIGATION THAT OCCURS OUTSIDE THE BORDERS OF SAO PAULO STATE

The measures analyzed in the construction industry coupled with the other technologies that make up the MAC Curve for the State of Sao Paulo (Section 4.1.2) total twenty strategies for the reduction of GHG emissions. These strategies are shown in **Chart 43**.

Table 34 presents the values that make up the MAC Curve.

Dematerialization and the approach from the consumption perspective show economic results and significant emission reduction potentials, especially in material-intensive industries (cement, lime and construction). This shows the relevance of exploring this possibility from the

Chart 43 – Marginal Abatement Cost Curve including construction



Source: Prepared by the authors (2017)

Table 34 – Values of the marginal abatement cost curve for Sao Paulo's industry including construction

Technology/low carbon measure	Marginal abatement Cost	Reduction of emissions 2014–2030
	(USD/tCO_2e)	($MtCO_2e$)
Construction: mixer	–212	5.63
Construction: ready-mix concrete	–189	2.99
Chemical: more efficient motors	–150	5.77
Chemical: LED	–145	0.57
Steel: preheating and continuous feed	–134	0.61
Chemical: Cogeneration	–111	16.46
Steel: direct current furnace	–102	0.27
Chemical: replacement of natural gas with reforestation wood	–75	4.79
Chemical: replacement of fuel oil with reforestation wood	–58	2.28
Chemical: ammonia	–27	0.06
Cement and construction: filler addition	–2	50.32
Chemical: nitric acid	2	0.84
Cement: pellets	10	11.62
Cement: RDF	10	11.62
Lime: Maerz furnace using torrefied biomass	12	0.13
Steel: TGR-MDEA	16	19.27
Lime: Maerz furnace using biomass in natura	17	1.09
Lime: CCS	29	2.54
Construction: industrialized mortar	120	6.37
Chemical: green ethene	1,174	0.54

political standpoint for achieving the reduction of emissions expected in the state. However, for the reduction of emissions to be truly effective, agreements and ways to account for emissions so that they are not simply transferred to another state of the federation need to be established. A consensus on this approach is necessary, with the support of all Brazilian states, and possibly also of the UNFCCC. Parallel to the reduction of material consumption, the alternatives that stand out in the analysis are those related to the reduction of energy consumption or fuel replacement, including, in this group, the use of municipal solid waste. This approach can also be a starting point for the discussion of emissions embodied in goods imported from abroad, which often compete with goods produced in Brazil and that are less intensive in terms of carbon emission.

7

Appendix B

Calculation of the Marginal Abatement Cost

This appendix presents the calculation of the marginal abatement cost (MAC).

MAC uses an incremental approach in which the values of economic results and of emissions between the BS and the LCS are compared, as already shown in Equation 1. The "result" in **Equation 1** consists of CAPEX, OPEX, energy cost and revenue, as explained in Equation 21. Because it is a total cost, CAPEX needs to be levelized through the CRF (**Equation 22**) and then added to the other annual costs. It should be stressed that, depending on the technology being assessed, each cost component may be present or not.

Equation 21 – Calculation of economic result within MAC

$$Result_i = CAPEX * CRF + OPEX_i + EC_i - R_i$$

Source: Prepared by the authors (2019)

Where:

$Result_i$	=	annual cost of the measure in year n	(USD)
CAPEX	=	total cost of measure investment	(USD)
CRF	=	capital recovery factor	(dimensionless)
$OPEX_i$	=	annual operation and maintenance cost in year n	(USD)
EC_i	=	annual energy cost in year n	(USD)
R_i	=	annual revenue in year n	(USD)

Equation 22 – Calculation of the capital recovery factor

$$CRF = \frac{r * (1 + r)^t}{(1 - r)^t - 1}$$

Source: Prepared by the authors (2019)

Where:

CRF	=	capital recovery factor	(dimensionless)
r	=	social discount rate	(%)
t	=	life of the technology	(years)
MAC_i	=	Marginal Abatement Cost in year i	(USD/tCO_2)
MIT_i	=	emission avoided by the low carbon technology in year i	(tCO_2)

The annual costs thus obtained, in general are different due to the variation of flows cost-benefit analysis over the years. The final MAC included in the MAC curve will be the weighted average of the annual MACs by the amount of CO_2 avoided annually, as shown the **equation 23**.

Equação 23 – Calculation of weighted MAC of low carbon technology

$$MAC = \frac{\sum_{i=1}^{n}(MAC_i * MIT_i)}{\sum_{i=1}^{n} MIT_i}$$

Source: Prepared by the authors (2019)

Onde:

MAC	=	Weighted Abatement Marginal Cost	(US$/$tCO_2$)
MAC_i	=	Abatement Marginal Cost in year *i*	(US$/$tCO_2$)
MIT_i	=	Emission avoided by the low carbon technology in year *i*	(tCO_2)

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