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# ANALYSIS OF THE IMPACT OF INCREASED EFFICIENCY OF COAL-FIRED POWER PLANTS IN CARBON DIOXIDE ($CO_2$) EMISSIONS

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**Abstract.** *Coal is the main fossil fuel used worldwide for the generation of electric power due to its low cost and high availability of reserves, and therefore must still be used for some hundred years as the main energy resource. The environmental impacts associated with the emission of pollutants from the process are of great relevance, the main pollutants being SOx, NOx, particulate matter, and $CO_2$. $CO_2$ emissions represent a major problem in planetary dimensions, given their influence on climate change. To glimpse a reduction of carbon dioxide emissions through changes in the fuel does not show as a viable alternative for most cases, thus, the optimization of the thermal conversion process by increased efficiency of coal-fired power plants has been studied, and technologies have already been applied. The study aims to quantify $CO_2$ emissions in both specific and large-scale terms, considering the use of different technologies, through the construction of 3 different scenarios with the hypothesis of using different technologies in the coal-fired generation units. The results indicate that the modernization of the global thermal coal park would provide a significant reduction of emissions, allowing the promotion of a low carbon matrix, without the need to abandon the use of mineral coal as a source for electricity generation.*

***Keywords:*** *Efficiency, Emissions, Coal, Carbon Dioxide, Climate Changes.*

## 1. INTRODUCTION

The beginning of the 21st century represented a period of unprecedented growth in the production and use of coal, mainly for the generation of electricity. According to (British Petroleum, 2017) the Asia Pacific region, which includes countries such as China, India, Indonesia, Malaysia, Vietnam, Australia, New Zealand, among others, was the main responsible for this boom in the coal market, from a consumption of approximately 2400 Mtoe in 2001, to a peak of almost 4000 Mtoe in 2013-2014.

According to the International Energy Agency - IEA (2015), coal accounted for 41.1% of the total electricity generated in the world, making it the main source of electricity generation, overcoming by almost twice the share of natural gas in the world's electrical matrix, second main source in the electric matrix.

According to (British Petroleum, 2017) the proven world reserves of coal in 2016 were sufficient to meet 153 years of global production, based on current production. This relation of reserves/production (R/P) is the largest of all fossil fuels. The specific R/P relation of each region varies significantly, for Europe and Eurasia, for example, it was almost 300 years, while for the Middle East & Africa region it was approximately 50 years.

The World Energy Outlook (2014) points out that the use of coal for electricity generation has a growth estimate of 0.5% per year between 2012 and 2040, with China and India's energy policy being a determining factor for the supply of coal. However, this growth is lower than the 2.5% per year that has been presented in the last 30 years.

An important role is played by coal in the global energy matrix, but the average efficiency of coal-fired power plants in most countries that use it varies significantly, from less than 30% to over 47% (LHV). This fact is due to many factors, including the age of the plants in operation, steam conditions in the cycle, local climatic conditions, coal quality used, operating and maintenance practices, and accessibility for the insertion of advanced technologies (IEA, 2016).

The basic thermodynamic cycle used in water-vapor systems, with technology marked by high degree of maturity, safety and with application since the end of the 19th century, remains the thermodynamic cycle of Rankine. The thermal efficiency of a steam cycle improves when the pressure and temperature of the steam at the boiler outlet increases and the pressure in the condenser decreases (Moran e Shapiro, 2009).

New projects of coal-fired power plants seek to optimize increasingly the use of thermal energy from the combustion of coal, and thus promote increased efficiency of the units, higher pressures and maximum temperatures in the thermal cycle are major factors contributing to this. Based on steam conditions (pressure and temperature) the coal-fired power generation can be divided into subcritical (main vapor pressure below critical pressure of 22 MPa), supercritical (pressure higher than critical pressure of 22 MPa), and ultra supercritical pressure (using supercritical pressure with vapor temperatures above 593 °C) (Kimura, 2011).

The use of supercritical and ultra supercritical conditions increases the efficiency of the Rankine cycle by the fact that this efficiency is directly proportional to the temperature and the vapor pressure during the process of adding heat to the cycle (Fan et al., 2018). An increase of one percentage point in plant efficiency is estimated at every 20 °C increase in the main vapor temperature (Beér, 2007). Currently have several years of experience in the use of ultra supercritical technology (USC), which reaches parameters of 300 bar / 600 °C / 600 °C, and results in efficiency of more than 45%. The efficiency gain provided by this technology refers to a reduction of about 15% in $CO_2$ emissions (Blum and Hald, 2002; Beér, 2007).

Increasingly stringent regulations, especially in relation to $CO_2$ emissions, has increased the search for improvements in plants that allow the gain of some percentage points of efficiency (IEA, 2011). The vapor conditions of the cycle consists in one factor that has the main impact on the performance of the plant, and this translates into differences in the levels of $CO_2$ and other pollutants that are emitted per kWh of electricity generated. In this way, as countries are making stricter their emissions standards, as well as pledging to reduce their $CO_2$ emissions following the agreements signed at the United Nations climate change conferences, the quest to establish a high- efficiency coal-fired fleet is in full development. (Motyka, 2016).

The Paris Accord proposed and formalized ambitious targets, beyond expectations of that time, with the goal of keeping global warming below 2 °C, with a goal of 1.5 °C. It also established measures to ensure that countries can adapt to climate change by promoting climate resilience. The proposal is that the peak of global greenhouse gas emissions be achieved as soon as possible and recognizes the greater difficulty of developing countries in achieving this goal. To achieve the goal of maintaining global warming below 2 °C, massive investments in infrastructure deployment of low-emission technologies are essential (Rojas, 2016).

According to Barnes (2014), upgrading existing plants and building new power plants with high-efficiency and low-emission (HELE) addresses concerns about climate change in two important ways. In the short term, upgrading existing low-efficiency plants by adapting them with HELE technologies and build the new capacity expected in high-efficiency plants will reduce $CO_2$ emissions in almost 20%, and in the long term, high efficiency and low emissions are the most appropriate options for a future adaptation of Carbon Capture Storage (CCS) technology.

According to the International Energy Agency - IEA (2012), a large number of low-efficiency plants are currently in operation, with more than half of all installed capacity having more than 25 years of operation and being relatively small (less than 300 MWe). Several countries established as one of the priorities to improve the efficiency of their coal-fired power station, countries such as Japan and South Korea, which started the installation of supercritical technology plants before 2000, today have high-performance coal-fired power plants with average efficiencies above 40% (LHV).

The article aims to present the concepts of Supercritical units, Ultra-supercritical, showing their peculiarities in relation to conventional thermal generation systems. In addition, it aims to present a quantitative study of the emission reduction, in specific terms (t/MWh), for Carbon Dioxide ($CO_2$), from the comparison of different technological scenarios.

## 2. METHODOLOGY

The study focuses on a $CO_2$ emission comparison for three scenarios, one of which corresponds to the basic technological option for coal burning and will be treated as a baseline scenario, the other two scenarios consolidate hypothetical scenarios of technological adequacy of the generation unit, the specific characteristics of each scenario are presented in Table 1.

Table 1. Operating data of the hypothetical generation unit for each scenario

| Characteristics | Scenario 1 | Scenario 2 | Scenario 3 |
|---|---|---|---|
| Operating Pressure | Subcritical | Supercritical | Ultra Supercritical |
| | 16 - 17 MPa | 24 - 26 MPa | 27 - 32 MPa |
| Temperature | 500 - 550 °C | 500 - 600 °C | 550 - 600 |
| Efficiency (%) | 34% | 43% | 47% |
| Combustion Technology | Pulverized Coal | Fluidized Bed | Fluidized Bed |

Based on the variability of the composition of the coal used all over the fleet worldwide coal thermal, and the great influence that this has on the quality and quantity of the products formed in the combustion, when developing a study to evaluate emission factors for coal units, the most appropriate is that a diversified sample of coal typologies should be used, so that the results obtained can be supported by reliable and representative data.

In this context, various coal compositions were selected to be objects of the study being specified by country and region where the deposit is located, such selection was based on the representativeness of the countries in the production and consumption of the fuel. Countries such as China, the United States, Australia, India, South Africa and Russia were selected because they are both among the 10 largest consumers and among the 10 largest producers of coal. Indonesia is not listed among the largest consumers, but has significant reserves, which makes its coal interesting to be included in the analysis. Brazil, despite not presenting itself neither as a major producer nor a large consumer of coal, was included in the analysis for the evaluation of the local reality as a significant item in the research.

Table 2. Elemental chemical composition data of mineral coal from different fields of different countries (Elementary Chemical Composition)

| Index | Country / Field / Region | Carbon | Hydrogen | Sulfur | Oxygen | Nitrogen | Moisture | Ash | LHV (kJ/kg) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | Austrália / AU-F / Queensland | 81.74% | 4.42% | 0.62% | 3.38% | 1.75% | 0.96% | 7.13% | n.d |
| 2 | Austrália / AU-G / New South Wales | 80.08% | 4.24% | 0.33% | 3.48% | 1.49% | 0.78% | 9.60% | n.d |
| 3 | Brasil / 99-035 / Rio Grande do Sul | 32.05% | 2.22% | 0.80% | 7.46% | 0.56% | 11.48% | 45.44% | 12820 |
| 4 | Brasil / Brazil 1 / Santa Catarina | 32.62% | 2.15% | 5.44% | 1.09% | 0.60% | 2.01% | 56.09% | n.d |
| 5 | Brasil / 02-429 / Paraná | 54.49% | 3.81% | 5.17% | 5.61% | 1.07% | 4.13% | 25.72% | 22800 |
| 6 | China / CN-35-34 /Shanxi | 66.81% | 3.70% | 0.34% | 4.18% | 1.12% | 0.98% | 22.87% | 26660 |
| 7 | China / CN-20-01 / Guangdong | 77.91% | 1.22% | 0.77% | 1.74% | 0.58% | 4.79% | 12.99% | 27750 |
| 8 | China / CN-24-05 / Liaoning | 44.38% | 3.01% | 0.37% | 9.85% | 0.61% | 10.69% | 31.09% | 18140 |
| 9 | China / CN-25-03 / Jiangsu | 52.98% | 3.76% | 2.54% | 6.64% | 0.86% | 8.93% | 24.29% | 21960 |
| 10 | China / CN-31-09 / Hebei | 65.60% | 3.75% | 1.90% | 4.52% | 1.12% | 3.22% | 19.89% | 27100 |
| 11 | China / CN-47-03 / InnerMongolia | 40.04% | 2.07% | 0.07% | 13.68% | 0.45% | 33.04% | 10.65% | 14640 |
| 12 | China / CN-53-01 / Shandong | 64.94% | 4.19% | 0.67% | 9.04% | 1.14% | 6.05% | 13.97% | 26360 |
| 13 | China / CN-85-16 / Guizhou | 77.22% | 4.88% | 0.64% | 5.54% | 1.44% | 2.10% | 8.18% | 32220 |
| 14 | Colombia / 71C/Manto 70 / LaGuajira | 78.72% | 5.18% | 0.39% | 9.71% | 1.52% | 3.09% | 1.39% | 32200 |
| 15 | Colombia / Colombia-0200 / Cauca | 60.16% | 4.45% | 5.12% | 6.18% | 1.05% | 1.70% | 21.34% | 25930 |
| 16 | Colombia / IGM 1077 / Boyaca | 80.85% | 5.19% | 0.73% | 4.64% | 1.89% | 0.85% | 5.86% | 34160 |
| 17 | Colombia / IGM 1238 / Cordoba | 61.64% | 4.54% | 0.58% | 16.10% | 1.41% | 12.81% | 2.92% | 24670 |
| 18 | Colombia / Interlab 400 / N. de Sant. | 78.79% | 5.69% | 0.51% | 6.91% | 1.58% | 1.35% | 5.17% | 33210 |
| 19 | India / SBT-19-R5B / MadhyaPradesh | 50.13% | 3.56% | 0.58% | 6.56% | 1.07% | 2.81% | 35.29% | 20450 |
| 20 | India / GR-II-98 / Rajasthan | 33.52% | 2.31% | 3.33% | 7.74% | 0.63% | 36.43% | 16.04% | 13770 |
| 21 | Indonésia / CQ01 / Oeste Sumatra | 73.16% | 5.41% | 0.51% | 9.14% | 1.35% | 3.10% | 7.33% | 30700 |
| 22 | Indonésia / CQ02 / Sul Sumatra | 50.69% | 3.74% | 0.24% | 16.86% | 0.77% | 18.02% | 9.68% | 20020 |
| 23 | Indonésia / CQ04 / Central Kalimantan | 48.38% | 3.42% | 1.00% | 14.39% | 0.94% | 26.49% | 5.38% | 19310 |
| 24 | Indonésia / CQ05 / Oeste Kalimantan | 57.47% | 4.10% | 0.37% | 13.06% | 1.31% | 19.36% | 4.33% | 23370 |
| 25 | Indonésia / CQ06 / Sul Kalimantan | 63.69% | 5.33% | 0.79% | 11.17% | 1.10% | 5.29% | 12.63% | 27170 |
| 26 | EUA /- / Colowyo | 67.54% | 4.46% | 0.35% | 13.74% | 1.40% | 7.96% | 4.55% | n.d |
| 27 | Rússia / -/ Sibéria | 64.03% | 5.04% | 0.52% | 15.20% | 1.30% | 6.08% | 7.82% | n.d |

Source: US Geological Survey (2015).

For the combustion process it was assumed that the coal has a moisture content of 1%. Thus, the correction of the mass composition of the coal was carried out and its lower heating value (LHV) was recalculated in kJ/kg from the Dulong equation as shown in Eq. (1).

$$PCI = 8140\,C + 29000\left(H - \frac{O}{8}\right) + 2220\,S - 600\,H_2O \tag{1}$$

For the estimation of the amount of $CO_2$ emitted, the combustion calculation was performed for the fuels presented, admitting: stoichiometric combustion, with air and fuel entering the ambient conditions (temperature of 25 ºC and Pressure of 1.01325 bar). Initially considering a unit thermal power for the plants and the fuel LHV, the necessary fuel supply rate was raised. From the combustion calculation the amount of $CO_2$ in kg/s emitted for each type of plant operating with fuels of different origins was found, and then the emissions in tons of carbon dioxide were estimated for each MWh of electricity generated.

The quantification of the results on a large scale refers to associating the production of electric energy from the use of mineral coal with the emission factor found for each scenario. In this way it can be verified how emissions on a global scale can be reduced only by the technological adequacy of the thermal coal fleet. Table 3 presents the scenario of electricity generation in 2013 for the countries studied, specifying the total electric energy generated annually by coal sources.

Table 3. Annual production of electricity.

| Country | Electricity Production | Coal | Production of coal electricity |
|---|---|---|---|
| | GWh | % of total | GWh |
| **Australia** | 249000 | 64.7% | 161103 |
| **Brazil** | 570300 | 3.8% | 21671 |
| **China** | 5422200 | 75.4% | 4088339 |
| **Colombia** | 64700 | 9.9% | 6405 |
| **Índia** | 1193500 | 72.8% | 868868 |
| **Indonesia** | 215600 | 51.2% | 110387 |
| **Russia** | 1057600 | 15.2% | 160755 |
| **United States** | 4286900 | 39.9% | 1710473 |
| **World** | 23354400 | 41.1% | 9598658 |

Source: (World Bank, 2014).

The objective is to estimate the emission factor, that is, how much is emitted each MWh of energy generated in a hypothetical unit of generation of energy, obtaining in unitary terms the emission of pollutants for different types of coal.

In this way, values can be used that can be used as object for large-scale estimations, with respect to new units that will be commissioned. Quantitatively demonstrating how significant the option for new plants with more efficient technologies enables the reduction in the environmental impacts generated by coal-fired power plants.

## 3. PRELIMINARY RESULTS

From the products obtained by the combustion of the mineral coal it was possible to obtain the CO2 emission factor, differentiated according to the coal composition. Figure 1 graphically expresses the results, allowing a visual analysis of the emission factor differences between different compositions, as well as the variation obtained between the scenarios.

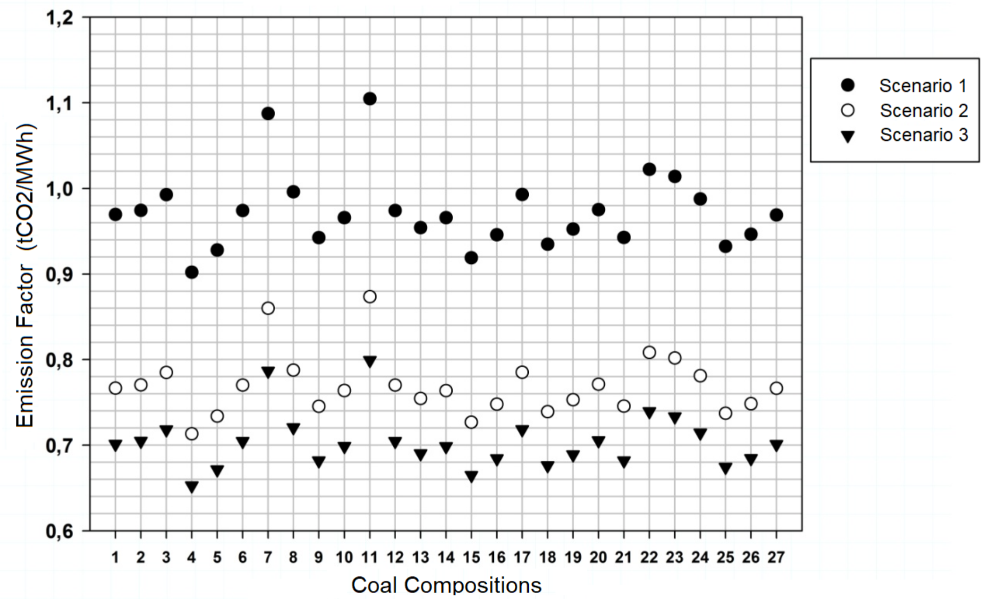


Figure 1. Graph of the $CO_2$ Emission Factor for each coal composition analyzed, in the 3 scenarios studied.

The "China / CN-20-01 / Guangdong" coal composition and the "China / CN-47-03 / Inner Mongolia" composition, indicated in the graph by the indices 7 and 11, respectively, were those with the highest emission factors with values of about 1.1 tCO2 / MWh. The first composition obtained this high emission factor due to the high contained carbon content, higher than 80%, while the second one presented high values due to the combination of two factors, the relatively high carbon content close to 60%, and the low calorific value, only 20709 kJ/kg.

The coal from the "Brazil / Brazil 1 / Santa Catarina" field, indicated by the index 4 in the graph, was the one that presented the lowest emission factor among the analyzed ones, as a result of the reduced carbon content, the lowest of all compositions, about 32% only.

China presented the highest average emission factor among countries with coal compositions analyzed, this fact indicates that for each 1MWh of energy generated by coal, China contributes on average with 0.9998 tons of carbon dioxide to the atmosphere when its units operate in a subcritical cycle, 0.7905 when in the supercritical cycle, and 0.7233 operating in an ultra-supercritical cycle.

With respect to the scenarios elaborated, one can notice a significant reduction in the emission factor of carbon dioxide. Scenario 1 is the reference, as described in the methodology is the so-called Baseline, consisting of a framework of use of conventional technology that does not allow high efficiency of operation of the unit. In this context, the other two scenarios that consist of the hypothesis of technological adequacy of the generation unit had the emission factor compared to the reference scenario, obtaining the following results:

- Scenario 2 presented a CO2 emission factor about 21% lower than the reference scenario, for all coal compositions analyzed;
- Scenario 3 presented a CO2 emission factor approximately 28% lower than the reference scenario, for all coal compositions analyzed.

Another interesting fact to be pointed out is the difference between carbon dioxide emissions for Scenarios 2 and 3. Scenario 3, which in hypothesis represents the generation unit operating with the highest efficiency achieved, can to reduce emissions by 9% in relation to Scenario 2.

Extrapolating the analysis through the association of the average values of emission factor with the production of electric energy from coal, we obtain the annual carbon dioxide emissions of each of the countries, for each of the scenarios studied, as can be Table 4.

Table 4. Annual average emissions of Carbon Dioxide

| Countries | Scenario 1 | | Scenario 2 | | Scenario 3 | |
|---|---|---|---|---|---|---|
| | Average (Mt/year) | Stand.Dev (Mt/year) | Average (Mt/year) | Stand.Dev (Mt/year) | Average (Mt/year) | Stand.Dev (Mt/year) |
| **Australia** | 156.562 | 0.558 | 123.793 | 0.441 | 113.257 | 0.404 |
| **Brazil** | 20.389 | 1.011 | 16.122 | 0.799 | 14.750 | 0.731 |
| **China** | 4087.521 | 251.616 | 3231.993 | 198.952 | 2956.930 | 182.020 |
| **Colombia** | 6.095 | 0.183 | 4.819 | 0.145 | 4.409 | 0.132 |
| **India** | 837.379 | 14.060 | 662.113 | 11.117 | 605.763 | 10.171 |
| **Indonesia** | 108.140 | 4.501 | 85.506 | 3.559 | 78.229 | 3.256 |
| **Russia** | 152.127 | - | 120.286 | - | 110.049 | - |
| **United States** | 1657.455 | - | 1310.546 | - | 1199.010 | - |

*Stand.Dev: Standard Deviation

For each of the countries, the standard deviation, which represents the range in which emissions can be varied based on the analyzed coal compositions, was obtained in addition to the average of annual emissions. High values of standard deviation indicate a great variability of composition for the country in question, indicating that the average emission estimate can vary greatly due to the more effective use of a given coal composition. Russia and the United States showed no deviation since only one coal composition was analyzed. Figure 2 presents the results presented in Table 4, allowing a better visualization of these. The results are presented separately in two graphs due to the scale.

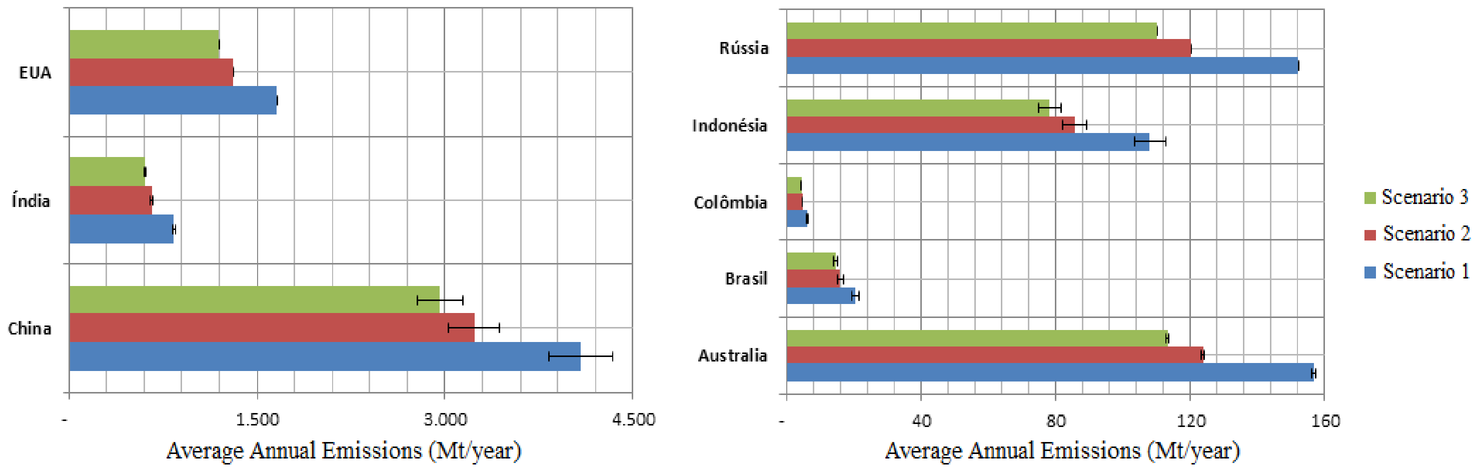


Figure 2. Annual average $CO_2$ emissions for China, the United States, India, Russia, Indonesia, Colombia, Brazil, Australia.

As can be checked, China is the country with the largest contribution to carbon dioxide emissions, totalizing approximately 4 billion tons per year in scenario 1. The United States and India emit approximately 1.5 billion and 800 million annually of tonnes of $CO_2$, respectively. When the $CO_2$ emissions of these three countries are summed together, an average annual emission estimate of more than 5 billion tons of $CO_2$ is obtained, an extremely significant value considering that global emissions from coal burning total about 8 billion tons, as the studies of the International Energy Agency of the year 2012 point out.

Subtracting the average emissions from scenarios 2 and 3 of the average emissions obtained for scenario 1 (Baseline), we obtain the emissions avoided, such values can be verified in Table 3.

Table 5. Annual emissions avoided (Mt/year)

| Countries | Sceanrio 2 Vs Scenario 1 | Scenario 3 Vs Scenario 1 |
|---|---|---|
| | Average (Mt/year) | Average (Mt/year) |
| Australia | 32.768 | 43.304 |
| Brazil | 4.267 | 5.639 |
| China | 855.527 | 1130.591 |
| Colombia | 1.275 | 1.685 |
| India | 175.265 | 231.615 |
| Indonesia | 22.634 | 29.911 |
| Russia | 31.840 | 42.077 |
| United States | 346.909 | 458.445 |

Figure 3 shows the results presented in Table 5, allowing a better visualization of these results.

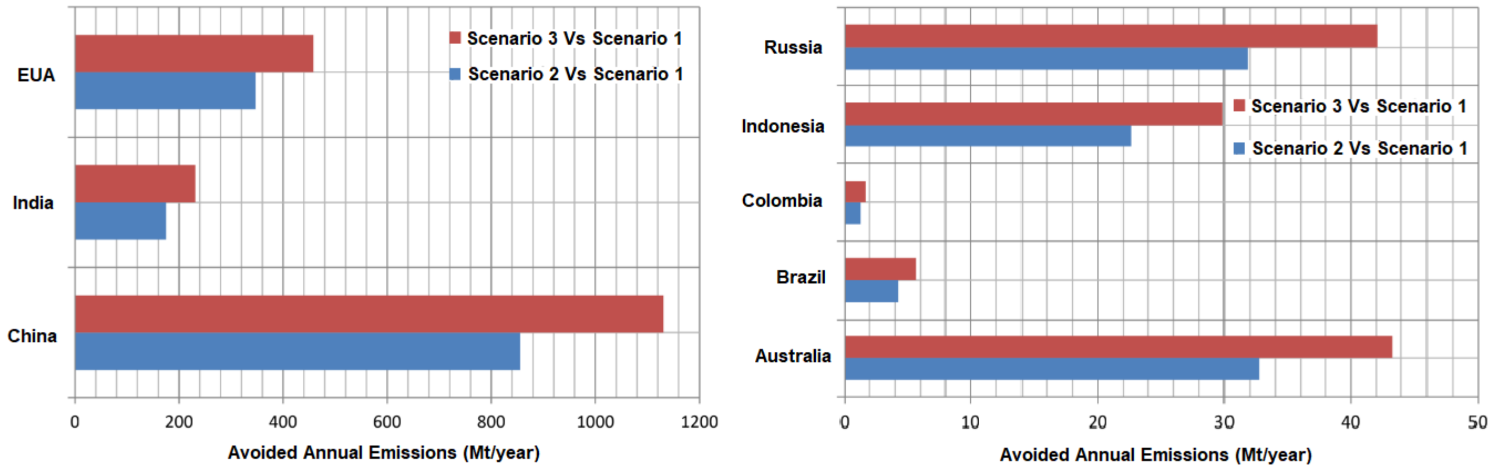


Figure 3. Annual avoided $CO_2$ emissions for China, United States, India, Russia, Indonesia, Colombia, Brazil, Australia.

The incorporation of technologies in the coal-fired thermal generation units, as suggested in scenarios 2 and 3, allowed a very significant reduction of emissions.

During COP21 the main discussion was the reduction of emissions of carbon dioxide, with focus on the energy sector, which is quantitatively the biggest "villain" when it comes to emissions of this gas. Among the discussions were the increase of renewable energies in the electric power matrix, making them increasingly representative, and also the realization of a technological improvement of the thermal generation units. China as the country with the largest contribution to $CO_2$ emissions has committed to reducing emissions by 40-45% by 2020 based on 2005 figures. The United States second largest emissions contribution has committed to reduce 26 to 28% of its $CO_2$ emissions by the year 2025, also based on 2005 figures. India, the third country with the highest generation of electric power for coal, has committed during COP21 to reduce its emissions from 20 to 25 % by the year 2020 (base year 2005). As shown in the discussions above, these countries could obtain a reduction of up to 28% of their emissions by the technological adequacy of their units, a very representative value.

Associating this large availability of coal, its relatively low and constant price in the market compared to other fuels, and its large share in the world's electric power matrix, it is not a probable reality to abandon the use of coal. Thus, the search for mechanisms such as Retrofit has become the focus of discussions on the clean use of coal. In this way one can align the idea of Retrofit as a CDM project. The Clean Development Mechanism (CDM) is a concept created by the Kyoto Protocol, and consists of projects that imply reductions in emissions additional to those that would occur in the absence of the project, in order to ensure that measurable benefits are achieved.

## 4. CONCLUSIONS

It was possible to verify through of the analysis of a sample of 27 different mineral coal compositions that each result in a differentiated emission factor, that has direct relation with the present carbon contents, besides the calorific power. For the carbon dioxide it was verified that it is not possible to establish a direct relation between carbon content and emission, since the carbon content in the fuel is directly associated to the calorific value of the same, being therefore the reduction of carbon in the composition of the coal which theoretically could provide reduction of the emission factor of carbon dioxide in practice does not occur, because a greater mass of coal is necessary for generation of a same amount of energy. China, India and the United States are the countries that currently contribute most to $CO_2$ emissions due to the burning of coal, emitting about 6.5 billion tons per year. It was verified that the hypothesis of modernization of the thermal park of these countries to use supercritical technology would enable the reduction of emissions of approximately 1.3 billion tons of $CO_2$ annually. The hypothesis of modernization using ultra-supercritical operation technology would avoid the emission of approximately 1.8 billion tons of $CO_2$ annually. The results provided the quantitative notion of how the modernization of the thermal fleet enables greenhouse gas emission reduction targets agreed at the global climate change conferences are possible to be achieved without there being a need to substitute coal for other uses sources of energy generation.

## 5. ACKNOWLEDGEMENTS

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