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Marginal abatement cost curve and break-even carbon price of fuel cell technologies in brazil

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Abstract:

Fuel Cells (FC) are considered to be one of the most promising energy technologies that have the potential to contribute significantly to sustainable energy supply and may help to mitigate the impact of greenhouse gas emissions. FC can be conveniently employed in conjunction with various fuels reforming process in order to make a more efficient and environmentally friendly use of the reserves of fossil fuels available. This paper investigates the cost-effectiveness and the carbon dioxide mitigation potential of different fuel cell technologies that are based on natural gas reforming in Brazil.

The method applied is marginal abatement cost (MAC) curves that graphically represent in for the economic attractiveness of a given mitigation option against its CO_2 abatement size. The MAC analysis of the FC options considered both social and private sector perspectives. For the social approach, a MAC was calculated using a social discount rate of 8%. The private approach (Break-even carbon price) is based on the expectation of return rates (15%) used not only by economic agents in the market, but also by financial institutions in Brazil.

The results pointed out that Solid Oxide Fuel Cell (SOFC) and Molten Carbonate Fuel Cell (MCFC) are economically attractive under social and private approach analysis. In turn, the Low-Temperature Proton Exchange Membrane (LTPEM) and High-Temperature Proton Exchange Membrane (HTPEM) have the highest values (US\$/CO_2 abatement) as compared to the other FC technologies.

The competitive frontier for FC energy production in Brazil is compromised by the high capital costs and low economies of scale. Although the stage of demonstration projects with Brazilian technology has already been completed, many components/accessories are imported, and the current import fees applied nearly double the costs of investment. Expected improvements in FC efficiency and lifecycle, in parallel with incentive mechanisms, i.e., purchasing power agreements, policies, and regulations can help to offset the capital cost of FC and to overcome the barriers that limit their penetration of the energy market in the country

Keywords:

Fuel Cell, Marginal Abatement Cost Curve, Break-even Carbon Price, CO_2 emissions

1. Introduction

In recent years, with the improvement of small-scale power generation units, the distributed generation concept achieved new dimensions in the energy industry. These units, located close to demand centers, both benefit consumers and support the economic operations of the existing power distribution system. Internal combustion engines and turbines, together with other emerging technologies, such as microturbines, photovoltaic panels and Fuel Cells (FC), provide a variety of options for distributed power generation.

FC have been acknowledged as a promising technology, environmentally friendly and efficient source of electricity and heat. The ability of FC to provide useful power and heat with high efficiency at local site, as from a variety of fuels has added attractivity to this promising technology. Even though most types of FC operate with hydrogen as fuel, this energy carrier can be produced from natural gas, landfill gas, electrolysis of water, biomass gasification, including waste, coal, among others. Of all the fuels used to feed FC, natural gas (NG) is currently the most widely used fuel.

Although hydrogen production from NG reforming liberates CO_2, the transformation of hydrogen into electricity by FC contributes to abating emissions (gCO_2/kWh) when considering the whole natural gas life cycle into electricity [1,2].

Compared to the centralized conventional generation and its efficiency, the FC technology presents negligible impacts on the air quality related to NG use. According to Breakthrough Technologies Institute report [3], the FC emissions from NG operations are so low that, in some areas in the United States, have even exempted natural gas-fueled fuel cells from air permitting requirements.

Nevertheless, new methods for capturing heat, associated with the availability of NG reserves, promoted significant economic improvements in hydrogen production. In this sense, FC has played an important role in the discussions about greenhouse gases (GHG) mitigation, faced with Climate Change Policies both in the world and also in Brazil.

Worldwide, carbon emission abatement goals, formalized, for example, by the Kyoto Protocol or the European Union 20-20-20 policy, challenge decision makers from different countries to reduce their CO_2 emissions at an effective cost. For this, Marginal Abatement Cost (MAC) curves are frequently used to illustrate the economics of climate change mitigation and have contributed to decision making in the context of climate change [4].

Under the perspective of costs and environmental benefits of a given power energy technology, MAC directly represents a set of technological options for developing a low-carbon economy and which impacts and costs these options might present [5]. The carbon MAC curves have not only the advantage of indicating the marginal cost of emissions abatement, for varying amounts of emissions reduction, but also allows calculation of the average and the total abatement cost [4].

The present study aims to estimate the cost and the CO_2 equivalent abatement potential deriving from power generation and use that could be avoided by using the Fuel Cells Technology (FC) in Brazil.

2. Scenario of the FCs application market

There are currently at least five different types of FCs, in various technological development stages and application in the market. In general, electrolyte and temperature distinguish the various types of FC. In a growing order of operation temperature, they are:

- Proton Exchange Membrane (PEMFC): 80° C
- High Proton Exchange Membrane Fuel Cell (HT PEM): 150°C
- Phosphoric Acid Fuel Cell (PAFC): 200°C
- Molten Carbonate Fuel Cell (MCFC): 650° C
- Solid Oxide Fuel Cell (SOFC): 1000° C

There are different applications of FC technologies, based on the power consumption by stationary equipment (commercial and residential use). As well as the use of hydrogen, originating in the reformer, as an input for refining or food industries, among others, as fuel to move electric engines in vehicles.

Since the rising trend of companies to adopt cleaner production strategies and the development of technologies that help to reduce their GHG emissions, numerous companies, both new and long-time users in the energy market have acquired FC, even in the order of multi-megawatts (MW), to supplement their energy portfolio.

In fact, the FC industry has attracted consumers from all areas of commerce. Several companies in this sector have become frequent customers, which purchase additional systems for their facilities. Organizations such as Apple, eBay, Coca-Cola and Walmart, have used the FC technology to provide their data processing centers, stores and facilities with reliable power [3].

Data presented in the Fuel Cell Technologies Market report[5], shows that two sectors have stood out in the use of FC technologies: commerce, including services (89%) and industry (11%). In these sectors, stationary applications for power generation are the major ones and in a smaller scale, mobile applications, specifically for transporting materials with forklifts.

In the commerce and services sector, 30% correspond to the telecommunication area (power backup for cell towers and installations), 18.5% to supermarkets (installation and forklifts), 17% to services and entertainment (i.e hotels, hospitals, among others), 12% information (electronic commerce) and 11% datacenter (computer and software companies, and banking facilities)

The U.S Department of Energy (DOE) [5] indicates that the annual installed capacity/in FC systems installations in the world market, particularly of stationary systems have been increasing. In 2003, there were 15 MW in contrast to the 105 MW of installed power/being installed recorded in 2012. In Brazil, the current FC installed capacity is 1.8 MW. According to the FC world database [6], all the applications surveyed are stationary, characterized by demonstration projects and distributed as presented in **Table 1**.

Table 1 – Installed power of FC technologies in Brazil

Year of installation	City	Company	FC	Installed Power (KW)
2001	Curitiba	Billing Center	PAFC	600
2001	Curitiba	COPEL Computer System Center	PAFC	200
2007	Curitiba	Erasto Gaertner Children's Hospital	PAFC	200
2004	Curitiba	Erasto Gaertner Children's Cancer Hospital	PAFC	200
2005	Itajubá	Federal University - Itajubá	SOFC	5
2002	Curitiba	LACTEC R&D facility	PAFC	200
2002	Curitiba	LACTEC Research Laboratory	PAFC	200
2002	Rio de Janeiro	Petrobras R&D Center	PAFC	200
Total				**1805**

Despite the investment made in the last ten years and the initial optimism of Brazilian Program for Fuel Cell Systems (ProCaC), the high costs of investments related to technological development, including equipment purchase, power production, as well as regulatory and financial constraints, consist the main barriers to the technology penetration in the Brazilian market [7,8].

On the other hand, from the perspective of government, research institutions and companies involved in the Brazilian R&D program, the technologies development for Hydrogen Economy will certainly contribute to a more efficient use of the national resources in the country. Their implementation is highly strategic from an economic, technological and environmental viewpoint [8].

3. Marginal abatement cost curve

Although MAC helps to assess the conditions in which a certain carbon mitigation proposal can be effectively implemented, there is not a single method for analyzing these options. Different perspectives may be used to inform the interested parties about the economic conditions under which the technologies may be used.

The construction of the marginal curves were based on the methodological approach of the analysis reported by the World Bank Brazil Low-Carbon Country: Case Study [4]. In this study, the cost per ton of carbon was calculated according to two approaches, namely, social and private, described as follows.

3.1. Social approach

The social approach provides a base for making a comparison of the effectivity of the mitigation options considered in the study. The calculation of the carbon marginal abatement cost take into account the Net Present Value (NPV) of the mitigation technology along the period determined to analysis, by applying a fixed discount rate.

The NPV of the mitigation technologies is given by the Annual Net Cost (ANCn) for each low-carbon option and the baseline, according to **1**.

$$ANC_n = \frac{INV \cdot r \cdot \dfrac{(1+r)^t}{(1+r)^t - 1} + AOMC_n + AFC_n - AREV_n}{(1+r)^{(n-2011)}} \qquad (1)$$

where,

ANC_n	net annual cost of the technology used in the reference scenario (2011 value) for year n, U$
INV	Total capital cost of technology employed in the reference scenario, U$
$AOMC$	annual operation and maintenance cost of the technology used in the reference scenario, U$
AFC	annual fuel cost of the technology used in the reference scenario, U$
AREV	annual revenue generated by the technology use in the reference scenario
r	discount rate
t	lifetime of the technology, years
n	year

The ANCn represents the difference between the annualized investment and the financial result, the latter given by the total revenue and the operation and maintenance expenses for implementing the option chosen, in relation to the discount rate.

Therefore, the annual marginal abatement cost of alternative technologies is the difference between the NPV of the ANCn of each technological option and the baseline, regarding the difference between the total carbon corresponding mass emitted and avoided (**2**).

$$AC_n^{technology} = \frac{ANC_n^{abatement} - ANC_n^{base}}{AE_n^{base} - AE_n^{abatement}} \qquad (2)$$

where,

$AC_n^{technology}$	abatement cost of GHG mitigation technology for year n, U$
$ANC_n^{technology}$	net annual cost of the abatement technology (2011 values) for year n, U$
ANC_n^{base}	net annual cost of the technology in the reference scenario (2011 value) for year n,U$
$AE_n^{abatement}$	annual GHG emission with the abatement technology for year n, U$
AE_n^{base}	annual GHG emission with the technology in the reference scenario for year n, U$
n	year

The MAC value thus refers to the maximum carbon abatement potential of the technological option, the graphical representation of which indicates the total reduction cost of each option in a given analysis scenario.

3.2. Private approach

As specified by De Gouvello [4], the private approach assesses the conditions under which the proposed measures could become attractive to economic agents deciding whether to invest in low-carbon technologies in lieu of the more carbon-intensive ones.

This approach follows the same logic of the carbon market established after the Kyoto Protocol, which starts a limit for emissions and the possibility of trading carbon credits. These credits correspond to an extra income for investors opting for less carbon-intensive technologies than the pre-existing ones.

The minimum incentive value for the mitigation measures (FC technologies) to become attractive to economic agents is given by the annual revenue generated by the alternative technology (REVn), applying the IRR expected in the sector (3). The result consequently expresses the cost per ton of carbon necessary to attain the income return rate (IRR).

$$REV_n^{technology} = k \frac{AE_n^{base} - AE_n^{abatement}}{(1+r)^{(n-2011)}} \qquad (3)$$

where,

k	1.00 U\$/tCO$_2$
$REV_n^{technology}$	annual revenue of GHG mitigation technology for year n, U\$
AE_n^{base}	annual GHG emission with the technology in the reference scenario for year n, tCO$_2$
$AE_n^{abatement}$	annual GHG emission with the abatement technology for year n, tCO$_2$
r	discount rate
n	year

That is; the market incentive is the value in US\$ per tCO$_2$ which breaks even the revenue and cost curves of the option, considering the IRR expected by the sector. This incentive can be understood as the technology Break-Even Carbon Price (BCP).

Both the emission abatement potential and the BCP of the options analyzed are recorded in a single graph to facilitate comparing the options. However, neither MAC nor BCP consider issues such as the improvement in air quality resulting from reducing GEE, or the different interdependencies applicable of the power system on the economy, the environment and society [9].

In this sense, we highlight that this analysis does not account all the externalities as it is not possible to quantify the major ones associated with each option measured at the present stage of the technology. To ensure the analysis consistency, only the monetary costs, and revenues were accounted, despite the possibility of certain externalities being critical factors in the decision-making.

3.3. Reference scenario, cost and discount rate

The reference scenario was defined by a partial replacement of the diesel generators, that is the baseline technology, commonly used in Brazil in stationary applications, such as prime power and standby/emergency, with FC technologies – mitigation options. The increment in the FC installed capacity, and the emissions that could be avoided due to this replacement were also recorded. The horizon analysis is ten years (2012-2022).

As an expectation of the growth in FC installed capacity (from 1.8 MW to 12.6 MW), the same rate identified for FC systems installed in other countries - 600% - was assumed. This increase is an estimate of the installed capacity growth rate in the world market, equivalent to the last ten years, according to data from the United States Department of Energy [5,10].

The installed capacity of generator groups in Brazil - from 90 to 2500 kW - had as a base only the data publicly made available by Cummins, whose participation in the Brazilian market generator groups is 53%. The applications in the different sectors are presented in **Figure 1**

The baseline technology installed power assumed, in this case, is 18MW, with a 3.8% annual expansion rate. The replacement of diesel generators with FC occurs gradually over the years of the period under study, according to the increment in the FC technology installed power.

The costs regarding the FC technologies refer to the costs associated with the stationary applications of FC systems, suitable for generating power in commercial or industrial buildings. The systems analyzed were configured for a combined heat-power operation. Given the technology maturity of each FC and the different application types in the market, the cost values of the technologies are associated with the corresponding variation in power capacity of the energy system, as well as to the thermal and electrical efficiency. The data considered within are presented in **Table 2**, in which is noticed that commerce and data centers are mainly sector that use diesel generators sets .

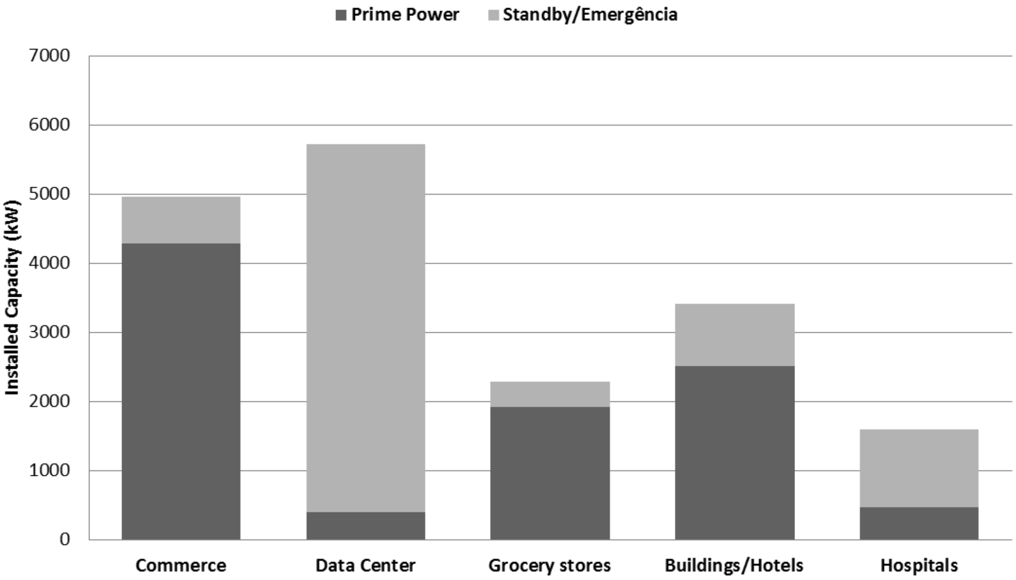

Fig. 1 – Installed power of diesel-fueled generator groups in different segments in Brazil.

Even though FC depends on the technology and the application types, the technologies analyzed share the same configuration characteristics, such as:

- Operating with natural gas and air;
- Reform system that converts NG in a hydrogen-rich reformed gas;
- Combined heat-power generation, thus involving heat exchangers;
- 41.5% capacity factor;
- Habilitated to be connected to the power grid.

Table 2 – Cost associated with FC technologies and operation characteristics

	unit	**PAFC[11]**	**LTPEM[12,13]**	**HTPEM[12,13]**	**SOFC[11]**	**MCFC[11]**
Power range	kW	15 - 500	1 - 10	1 - 10	500 - 5000	100 - 500
Electrical installed power	MW	0,3	0,1	0,1	1,0	0,5
Capital costs, installation	U$/kW	3911	7291	7915	3911	3259
Operation and Maintenance (O&M) Cost[14]	U$/kWh	0,0189	0,0369	0,0369	0,0189	0,0189
Electrical efficiency	%	45	38	42	53	50
Thermal efficiency	%	47	47	43	36	34
Global efficiency	%	92	85	85	89	84
Energy rate Th/Elec	GWh_t/GWh_e	1,0	1,2	1,0	0,6	0,7
Operation time	hours	60.000	30.000	30.000	60.000	60.000

[11] Final Report of the project Green-X: Research project within the 5th Framework Programme of the European Commission, DG Green X Research Project.

[12] Independent Review of Systems Integration, published for the U.S Department of Energy and Fuel Cell Program.

[13] Maximum values of O&M costs for PEMFC - Fuel Cell and Hydrogen in Sustainable Energy Economy/ Roads2HyCom Consortium.

[14] Natural gas cost – comercial use/ from 0,05 U$/kWh to 0,09 U$ /kWh (Gross Calorific Value 9.400 kcal/ m^3 – Deliberação ARSESP 284).

Given that mass production leads to a reduction in capital costs due to the system growth and the annual production rate [14], the model adopted to establish the expansion costs of FC technologies along the period analyzed and in function of the increase in power capacity, were based on the determination of the PEMFC technology learning curve presented by Tsuchiya & Kobayashi [15]. Following to the relative costs (U$/kW) over 2012-2020, the data were interpolated by an exponential function to determine the cost of expansion for each FC.

The import costs associated with purchasing the FC technologies modules in Brazil were also applied to the expansion costs. Particularly, concerning the HTPEM and the steam methane reforming system, the capital costs and O&M were surveyed as from the R&D Project – Cooperation Agreement involving BG E&P Brazil, Hytron and Instituto Inova.

The greenhouse gases (GHG) originating from generation and use of power that could be avoided by using FC technologies were accounted based on the CO_{2eq} life cycle emissions of the baseline technology and the mitigation options; i.e., from the extraction of the natural resource up to the power system decommissioning. This approach allows a more systemic assessment of the emission reduction potential (**Table 3**).

Table 3 –Life cycle emissions of the FC technologies studied

Technology	Emission factor [tCO_{2eq}/kW] (1)	Emission factor [tCO_{2eq}/kWh] (2)
PAFC	0,9900	
HT PEM	0,6415(3)	
MCFC	0,3830	
LT PEM	0,2930	
SOFC	0,3830	
SMR		4,80E-05

(1) Emissions factors associated with each life cycle technology studied– cradle to grave approach [16]

(2) Emission factor of hydrogen life cycle production via natural gas reform gathered from R&D Project – Cooperation Agreement involving BG E&P Brazil, Hytron and Instituto Inova – Life Cycle Assessment of Fuel Cell Powered by Natural Gas Reform

(3) Emission factor calculated from emissions average of PAFC and LTPEM

The corresponding costs of the diesel generators, as well as the emission of $CO_{2eq.}$ are presented in **Table 4**.

Table 4 – Life cycle emissions of diesel generators and costs

	Unit	Diesel
Power range	kW	40 - 500
Installed electrical power	MW	0,1
Installation cost	U$/kW	383
O&M cost (1)	U$/kWh	0,009
Emission factor (2)	tCO_2/kWh	3,05E-04

(1) Diesel oil cost 0,31 U$/kWh based on diesel generator consumption [17]

(2) Emission factor of life cycle diesel [18]

The 8% social discount rate applied to the study is the same value invested by the PNE 2030 for the Brazilian National Power Plan [19]. This rate is used for projects financed by the National Bank of Economic and Social Development (BNDES).

3.4. FC technology application sectors and internal return rate (IRR)

For the definition of FC technology application sector and its respective internal return rate (IRR) expected by the sector agents, the current applications of the technology in Brazil and the world were considered. Based on the identification of the FC technology application, two sectors are predominant regarding its use, specifically, commerce and industry.

In both sectors and independently of the subsector, the IRR expected is 15%. This sectorial IRR value was measured by De Gouvello [4], aiming, as herein, to assess the conditions in which a technological option for reducing emissions may be attractive from the economic agents perspective in Brazil.

Besides the social discount rate and the IRR, other economic parameters were used, such as the US dollar and the Euro exchange values in order to converting the values obtained in R$ related to the costs of the technologies in Brazil.

4. Results

4.1. Emissions of CO_{2eq} and costs

In the reference scenario, the replacement of diesel generators with FC technologies corresponded to an annual average of 6.4% of the total generator power installed year after year. Based on the capacity factor established here of 41.5%, the total hours of annual operation is 3636 h.

The full emissions over the years from the baseline technology- diesel generator - were 1.62 10^6 ton of CO_{2eq} for a total 5.32 10^6 MWh.. While the average of emissions produced by the generators and FC technologies (mitigation option) together were 1.53 10^6 ton of CO_{2eq}, about 6% less when compared to the baseline (**Figure 2**).

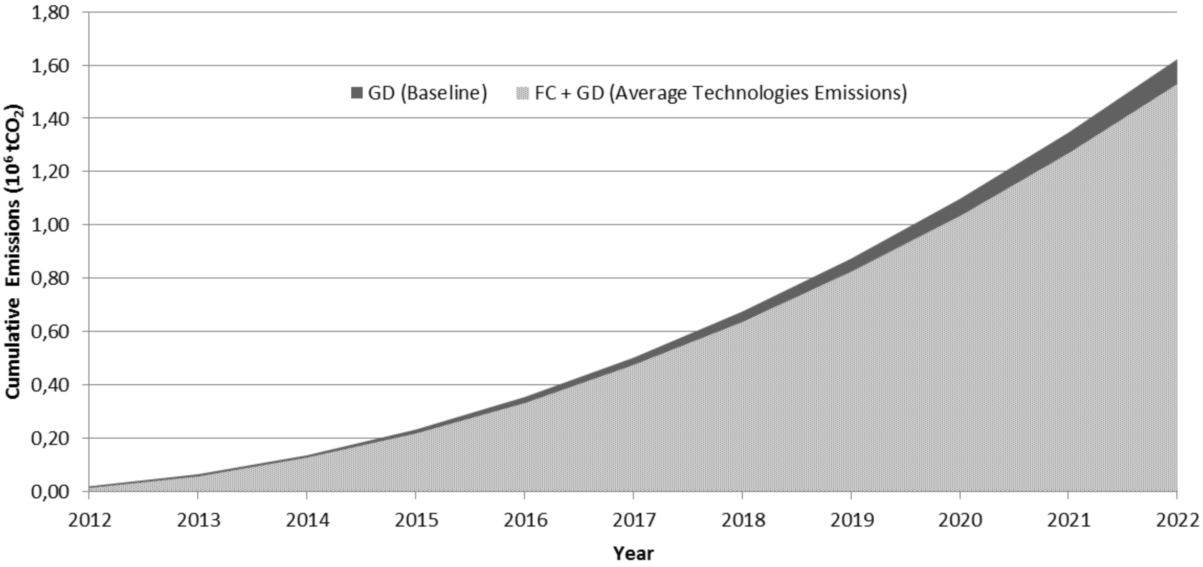

Fig. 2 – Emissions of diesel generators and FC technologies installed power (2012 -2022)

With regards to the total energy cost, the MCFC technology presents the lowest total cost (U$/$kWh_e$), as compared to the other FC. The progressive abatement in MCFC annual costs is observed to lead to a total cost 14% smaller than the diesel generators right in its 4th year. In contrast, only at the end of the period analyzed does the total annual cost of HTPEM break even with the baseline technology cost.

In general, the production of power with the FC technology is affected by the high power generation costs (an average U$1.57 per kWh) when compared to other conventional power generation sources, as is the case of diesel generators (U$ 0.16 per kWh). The high FC power generation cost is given, among other technical-economic aspects, by the high capital cost and the low economy of scale.

Additional barriers include the purchase of equipment. Although the design and demonstration stage with the Brazilian technology has already been reached, a number of components/accessories are imported, and the current tax rates applied double the investment costs practically.

4.2. Carbon marginal abatement cost and Break-even Carbon Price curve

In the marginal abatement cost and the break-even carbon price curves, both MCFC and SOFC technologies are economically attractive. Although PAFC presents a negative MAC value (-U$ 38.23 per tCO_{2eq} avoided), the same is not observed in the value found for BCP (U$ 91.07 per $tCO2_{eq}$ avoided). **(Figure 3)**

That is, high-temperature cells (MCFC and SOFC) shows a better performance related to the mitigation abatement cost and the return on investment since they present smaller emission factors (0.38 tCO_{2eq}/kW) than PAFC (0.99 tCO_{2eq}/kW) and the same magnitude of cost (**Figure 4**). This indicates the reason for certain technologies, for which the abatement cost is effectively viable, not being immediately implemented by economic agents, as they presuppose an incentive to return the investment made.

HTPEM presented higher marginal abatement costs (U$798.91 per $tCO2_{eq}$) and break-even carbon price (U$1817.90 per $tCO2_{eq}$) than the other FC.

The main factors influencing the values obtained by HTPEM are related to the high cost of investment or capital, associated mainly with technological maturity. Consequently, the economic viability of this option will largely depend on technological advances related to significant cost reductions.

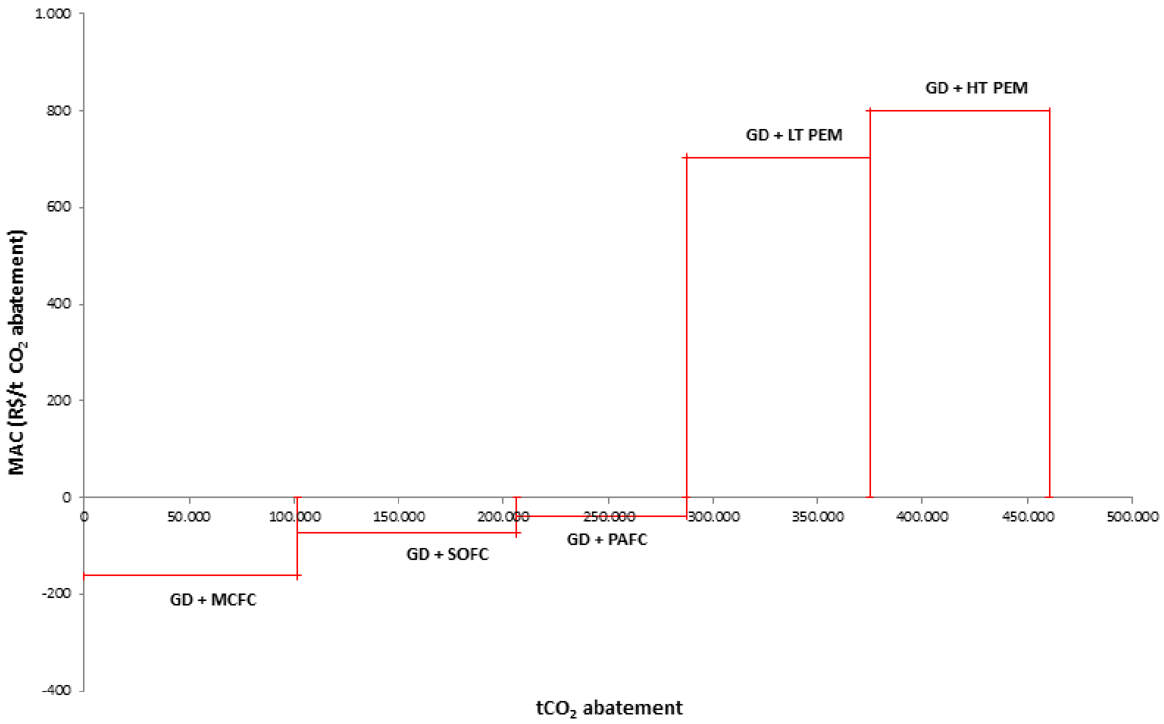

Fig. 3 – Marginal abatement curve - (2012-2022)

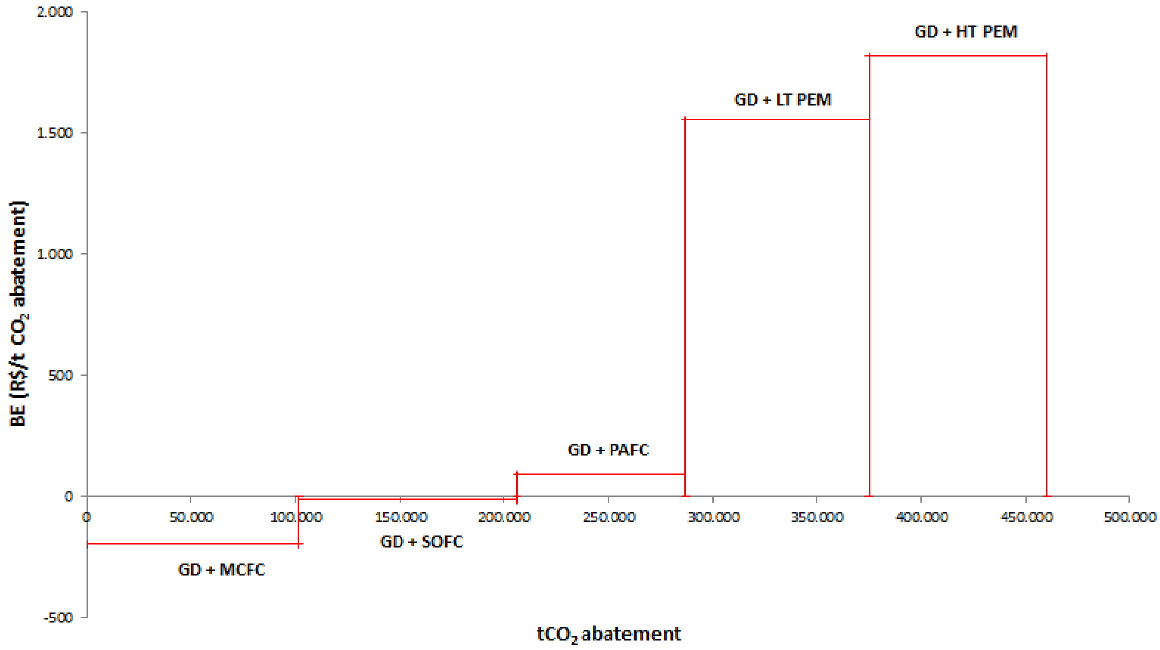

Fig. 4 – Break-even carbon price - (2012-2022)

The total incentives necessary for the HTPEM technology, for example, to represent an economically attractive mitigation option to the agents in the application sectors is about U$ 54 million in a 10-year period or 5.4 million a year (**Figure 5**). That is, in the absence of income deriving from selling carbon credits; the incentive value is U$ 629 per tCO_{2eq} or less.

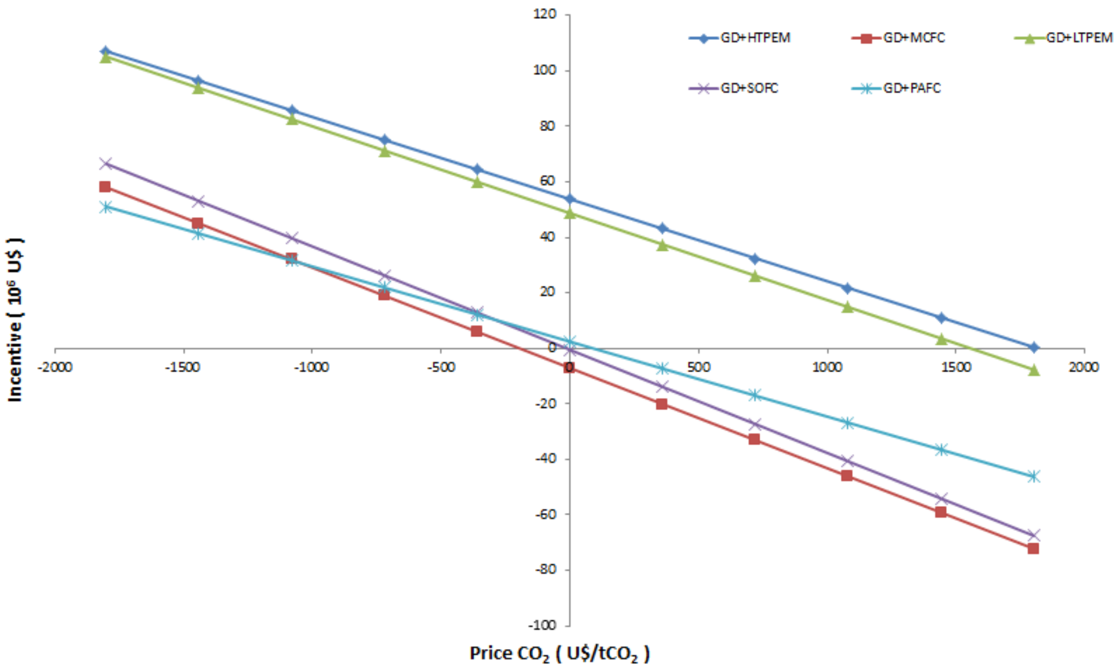

Figure 5 – Financial incentives for implementing the FC technology - (2012-2022)

The incentive measured for HTPEM is observed to be greater than the values obtained for the other FC. Even though the HTPEM technology is not economically attractive under the social and private approach, the economic improvements deriving from energy efficiency, cogeneration and distributed generation, as also expected for the other FC, imply expectations of benefit or positive impacts not considered in the analysis and which may compensate for this high value.

As aforementioned, to ensure evenness in the analysis, only the monetary costs, and incomes were accounted since a consistent assessment of externalities is not possible given the different development stages of the FC technology.

Finally, the introduction of mitigating technologies rather than conventional applications is a slow, high-cost process, which will not be implemented solely by the private sector, since such changes are mainly directed by social and political aspirations opposed to market indicators. As a consequence, besides investments by the private sector, political compromise, and strong financial support by governments are necessary to overcome existing barriers.

5. Conclusions

In the scenario of the analysis, from the private sector perspective, FC technologies, whose MAC and BCP are negative, present a better cost-benefit ratio. These technologies do not require incentives, as they can generate economic gains in power at their implementation, thus being configured as a win-win situation.

Clearly, not all FC technologies, such as HTPEM, can be analyzed from the private sector point of view; on the contrary, governmental incentives may be provided for other reasons, besides CO_2 emission abatement.

However, this perspective is valid to demonstrate where incentives can be more adequately applied or are more necessary, and where other mechanisms, such as regulations and standards, can be more appropriate than the carbon market.

Therefore, the economic incentives for making HTPEM attractive, for example, as well as LTPEM, are not necessarily selling carbon credits. Incentive mechanisms applied in other countries, such as power purchase agreements, credit rates, policies and regulations for reducing emissions, as well as the use of less carbon-intensive power generation technologies, may help the carbon mitigating options, such as FCs, to overcome the barriers limiting their penetration in the Brazilian energy market.

Acknowledgments

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