Photosynthesis, a Natural Process for Decarbonization of the Steel Industry

D. Calais1, R. S. Sampaio2

[1]Forest Engineer, UFV – 1969. Technical Assistant to SINDIFER – Union of the Iron Industry in the State of Minas Gerais. astec@sindifer.com.br

[2]Metalurgical Engineer, M.Sc., Ph.D., CEO RSConsultants Ltda, Minas Gerais, Brazil, ronaldo.issbrazil@gmail.com

Keywords: green pig iron, oxygen regeneration, natural CO_2 capture, storage, and use, sustainability of biomass use in ironmaking

Abstract

Sustainable photosynthesis is the Nature solution for reduction of CO_2 emissions. Forest plantations are established and managed under the most severe environmental regulations and sustainability guidelines. And so are the operations for wood conversion into charcoal and its transportation to ironmaking facilities to produce merchant iron. Social benefits reach regions where job opportunities are scarce. The advanced Brazilian forestry technology guarantees forests cultivated on poor soils, in areas with low rainfall and unsuitable for annual crops. Therefore, forest plantations are never in competition with food production. This paper focuses on social and environmental benefits of steel industry based on biomass.

Introduction

Global warming is, undoubtedly, one of the most serious concerns of humankind in the present world. As it is widely known or agreed, carbon dioxide (CO_2) is the main of the greenhouse gases. Efforts have been made to reduce the CO_2 concentration in the atmosphere and thus to control the increasing temperature. None of them has proved to be as efficient as that performed by Nature, i.e., the photosynthesis. This miraculous biochemical reaction is conducted by all the vegetables in their growing process, however, because of their large foliar surface and their long-life cycle, trees are particularly effective in capturing CO_2 and releasing O_2. An added advantage must be reinforced. Photosynthesis is an endothermic reaction that occurs under the sunlight. At night, respiration takes place, which, unlike photosynthesis is an exothermic reaction. The conclusion is clear, the trees, whether in natural or planted forests, are also effective in reducing the thermal amplitude. Even under a small group of trees, one can feel how pleasant their shade is, when compared to the shade under a roof.

Based on photosynthesis, biomass in permanent growth is the natural machine for Carbon Capture, Storage, and Use and oxygen regeneration. These natural resources are the driving forces behind the Brazilian producers of primary iron.

The use of small and medium-sized farms to supply an expressive part of their needs of eucalypt wood is also a feature that intensifies biodiversity. Eucalypt plantations are only part of a diverse vegetation. Pasture, food crops and native preservation areas are also included in the land use of medium-sized properties.

Figure 1 illustrates a system based on photosynthesis where a substantial number of actors are in place to make possible the growth of the necessary amount of wood. The carbon fixated in the stem -is only a part of the total carbon that is fixated by this complex natural living ecosystem.

Therefore, growing trees seems to be an effective and feasible alternative to strengthen the fight against global warming, thus controlling climate change. This alternative proves to be particularly attractive when large tree plantations can be used for industrial purposes, taking care of the necessary biodiversity that contributes to more fertility of the soil reducing the need of fertilizers and bringing more social and environmental benefits, in addition to wealth.

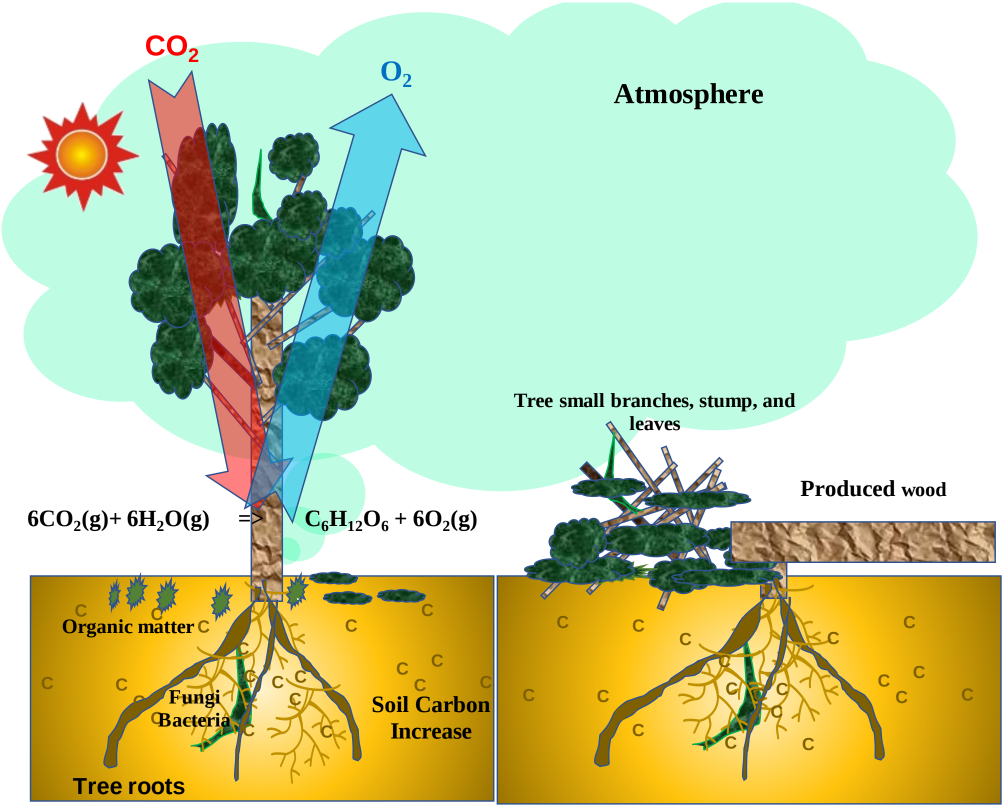

Figure 1. Illustration of natural carbon capture and storage with oxygen regeneration driven by solar energy.

Charcoal Based Primary Iron Industry

Charcoal, a product resulting from the dry distillation of wood, is an important input for industrial sectors, such as the pig iron, steel, and ferroalloys industries.

Brazilian steel industry based on charcoal is the only one in the world, and, because it utilizes exclusively charcoal originated from planted forests, it contributes decisively for the environmental balance, being also a key factor for social inclusion as it generates jobs in all levels of society. It is also especially important to highlight that forest activities always bring improvement to the HDI - Human Development Index – of a region because the job offers occur in regions where job opportunities are normally scarce.

As already mentioned, forest plantations are particularly efficient in capturing CO_2 and releasing oxygen. In a system of sustainable yield, for each hectare being harvested there are at least six in growth phase, cleaning the air and softening climate changes. It is always advisable to remember that charcoal is a renewable source of energy. In times of greenhouse effect and global warming, charcoal-based steelworks should receive dedicated support and incentives from Brazilian authorities and from the national and international environmentalist communities as well. This is the only industry capable to produce essential goods for development while it cleans the atmosphere. Therefore, pig iron produced with charcoal from sustainably planted forests is properly called green pig iron.

Additional Investments

The huge environmental benefits of green pig iron do not come for free. The charcoal used by these plants comes from planted forests, and this means significant and permanent investment in land, plantings, and forests maintenance. Forest plantations constitute therefore the wood/charcoal supply system. Investment and maintenance costs cannot be stopped when the pig iron market is in low demand. Plants utilizing fossil coal do not have those additional costs. Thus, considering the known benefits of green pig iron, it is fair to claim a higher price for it, when compared to coke pig iron.

Brazilian Forestry

Nowadays, no one would seriously conceive the economic development of a country if it were not on sustainable basis. This premise becomes particularly true when applied to countries in development. Brazil is among the few countries with great availability of anthropized lands suitable for forestry. This availability of land associated with the highest forest yields in the world results in perfect combination of production factors.

Despite being named after a tree, Brazil only realized its immense forestry potential after Law 5,106/1966[1] which granted fiscal incentives for reforestation. These incentives ended in late twentieth century, when forest plantations became competitive. The learning period with already cultivated exotic tree species was short. A perfect cooperation between tree improvement and forest fertilization enabled competitive yields on poor soils in low rainfall areas. Therefore, the highest forest yields mentioned above do not only result from the favorable natural conditions, but also from the persistent work of researchers and the indispensable financial support of forest entrepreneurs.

Forest Plantations in the State of Minas Gerais

Minas Gerais is the state that has the largest area of forest plantations in Brazil, with 2.24 million hectares of eucalyptus trees[2], composed of the genera *Eucalyptus* and *Corymbia,* here indistinctly called eucalypts. In a state with so many different site indexes, the yields, of course, cannot be the same everywhere. An extensive survey conducted by Canopy Remote Sensing Solutions indicated that productivity in Minas Gerais may vary from 20 to 40 $m^3.ha^{-1}.yr^{-1}$. While collecting data for her M.Sc. degree, Pereira (2012)[3] found an average yield of 35.9 $m^3.ha^{-1}.yr^{-1}$ and an average density of 0.558 $g.cm^{-3}$ for six clones studied in northern Minas Gerais. As it is known, the yields in commercial plantations are never so high as they are in experiment plots. Therefore, 35 $m^3.ha^{-1}.yr^{-1}$, equivalent to 19.5 tons of dry wood per hectare per year is considered a reasonable average for the entire state. The wood from these plantations is used for pulp, chipboard, furniture, treated wood (fence posts, electric poles, corrals, sheds), firewood, pellets, sawmills and for the manufacture of charcoal. According to the *Instituto Estadual de Florestas*[4] (State Forestry Institute), in 2021, circa 35.7 million cubic meters of eucalyptus wood were used to manufacture around 24.6 million cubic meters, or 5.4 million tons of charcoal in Minas Gerais. The density of charcoal varies according to the quality of the wood; 220 kg per cubic meter is an average bulk density accepted. Apart from barbecue grills and small artisanal forges, this charcoal is totally consumed by pig iron mills, steel mills and ferroalloy industries.

Eucalyptus forests are usually harvested in two rotations, eventually in three. The average yield, of course, decreases in the second and third clearcut in the cases where reinvestments in fertilizations do not take place.

Units: The forestry sector primarily deals with volume. The change from volume to mass requires the concept of density, and wood density varies widely. *Eucalyptus* and *Corymbia* are two genera of plants with hundreds of species each. The density of their species varies between them and even between clones of the same species. An enlightening example of transforming volume into mass is duly addressed in further section.

Environmental Licensing: Forest Plantations

Like any other enterprise, a forest plantation may not be established without a previous environmental licensing. In Minas Gerais, this licensing is granted by the State through its State Council for Environmental Policy – Copam, which, by its turn is made up by members of government, industrial associations, and non-governmental organizations – NGOs. Licensing requirements vary with the planting area. In any case, the entrepreneur must initially comply with all legal restrictions on land uses. Main restrictions are the **Legal Reserve – LR** and the **Permanent Preservation Areas – PPAs**. In Brazil, the percentage of LR varies according to each biome where the forest plantation will be established. In Minas Gerais, 20% is the percentage for the whole state. The PPAs fulfill the role of preserving the water resources, the landscape, geological stability, biodiversity, protecting the soil and ensuring well-being of human populations. In general, LRs and PPAs occupy about 45% of a rural property. Considering that 5% is the standard percentage of service areas, it can be said that forest plantations do no not occupy more than 50% of the entire property. The conclusion is obvious: at least 45% of the land in kept untouched and additionally protected from fire and hunters.

Figure 2 illustrates a typical eucalyptus plantation and its neighboring native vegetation. As already mentioned, Legal Reserve and Permanent Preservation Areas cover, on average, 45% of the gross area. Therefore, the sustainable forest business is also a permanent and renewable machine to capture and store carbon and release oxygen. The long-term harvest cycle and the necessary soil fertilization guarantee extra carbon fixation in the soil and roots. It is never too much to remember that forest plantations indirectly protect native forests.

The wood applied for charcoal production represents less than 30% of the total carbon fixated in the biomass produced. This means that the branches and foliage remain on the ground where they decompose and are incorporated into the soil. Added to the roots, they represent 40% of the biomass that remains indefinitely in the soil. The vegetal is a CCU (Carbon Capture and Utilization) machine and a sizable portion of the fixated carbon is to increase the soil biodiversity life through fungi and bacteria action producing soil organic carbon. These additional benefits to the environment, which contributes to counterbalance GHG emissions, must be considered in the accountability of CO_2 emission/reduction. The oxygen regenerated back to the atmosphere must also become part of the CO_2 equivalent accountability. This arithmetic and thermodynamic flaw of IPCC CO_2 equivalent accountability must be corrected to bring the fair value of the sustainable photosynthesis as an efficient tool for Carbon Capture and Storage. Sampaio *et al*. (2022)[5].

Figure 2. A typical forest plantation and the respective Legal Reserve – *Photo by Plantar Reflorestamentos S/A.*

Charcoal Production

As well as the implantation of forest stands, charcoal plants also need environmental licensing to start operating. Licensing requirements depend on the forecasted annual production of charcoal. Annual productions from 50,000 m³ (11,000 metric tons) to 70,000 m³ (15,400 metric tons) are classified as small; from 70,000 (15,400 metric tons) to 100,000 m³ (22,000 metric tons) as medium size; over 100,000 m³ (22,000 metric tons), as large size.

Regardless of the amount produced and with a view to reducing the atmospheric emissions and improve process yields, procedures must be observed at the Charcoal Production Unit (CPU):

- Keep the moisture content of the wood to be kilned below 40%.
- Ensure the structural integrity of the kilns, preventing unwanted leakages.
- Keep the wood free of residues such as oil, soil, debris, and branches.
- Keep the ground clean and the control holes (on the wall of the kiln) clear before filling the kiln.
- Maintain an average volumetric yield that may vary according to monthly production but never less the 1.75 m³ of wood per 1.0 m³ of charcoal.
- Start the implantation or prove the existence of an arboreal curtain around the CPU.

In Minas Gerais, only the wood from planted forests is used for charcoal manufacturing, and Figure 3 shows a typical Charcoal Production Unit. To produce charcoal without promote methane emissions the sector developed simple and practical ways and means to make it utilize the traditional cylindrical masonry kilns connected to a chimney where a full incineration of the carbonization off volatiles is complete combusted utilizing the small wood wastes generated in the carbonization sites (1 chimney for each four kilns). The resultant ashes at the base of chimney kiln are used as fertilizers in the new seedlings breeding.

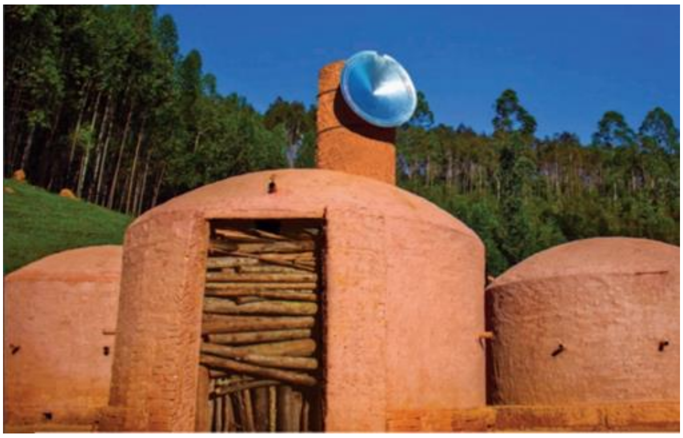

Figure 3. A typical Charcoal Production Unit – CPU.[6]

Social Benefits

Due to the characteristics of its industrial operations, pig iron and steel industries are activities that require intensive workforce, being, therefore, great generators of job opportunities. While utilizing charcoal as thermo-reducer, these industries triple their capacity to generate jobs in the establishment and maintenance of forests, in the harvesting operations, transportation of wood, and, at last, in charcoal manufacturing and transportation.

Charcoal consumption by the pig iron industry in Minas Gerais

Figure 4 presents the statistics of SINDIFER group of companies, independent merchant pig iron producers of Minas Gerais State, where charcoal consumption showed steady increasing over the last few years.[7]

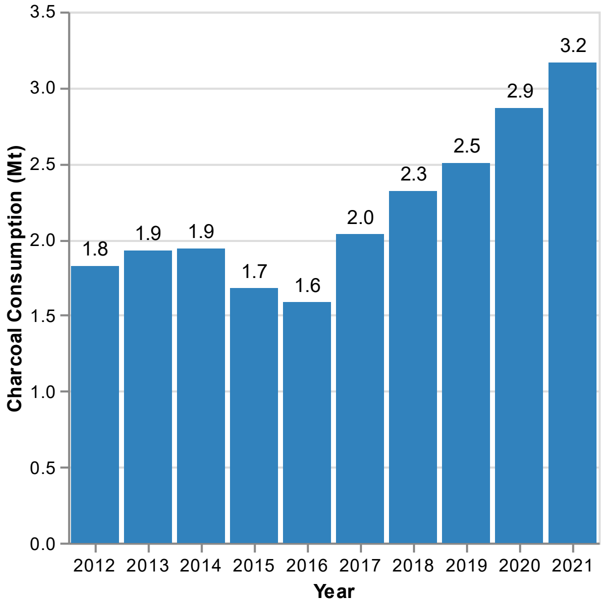

Figure 4. Charcoal consumption by the merchant pig iron industry in the state of Minas Gerais, Brazil. Notice that the values are in millions of metric tons.[7]

Job Opportunities

Employments generated by the production of pig iron with charcoal by independents plants in Minas Gerais and by the respective forest sector are indicated by Figure 5 for the years of 2020 and 2021; more than 118 thousand positions in 2021. It should be reaffirmed that these job offers at the forest sector take place in regions where job opportunities are scarce.

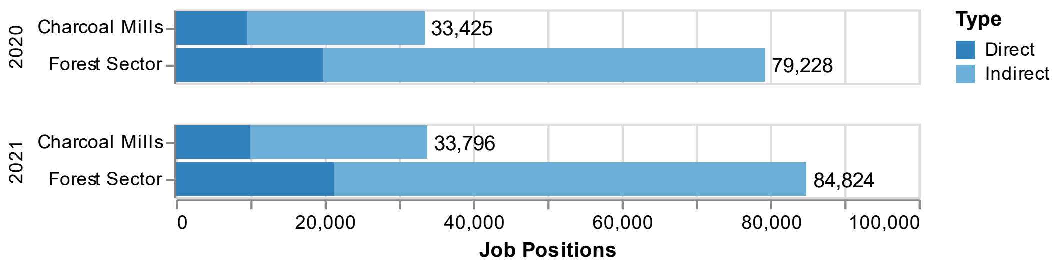

Figure 5. Labor demand from merchant pig iron independent producers in the state of Minas Gerais, for the years 2020 and 2021.[7]

Example for 1,000 Metric Tons of Pig Iron

As said above, 35 $m^3.ha^{-1}.yr^{-1}$ is considered a reasonable average yield for the eucalyptus in the entire state of Minas Gerais. This yield is a good reference but not enough. The density of the wood is the main indicator of its quality for making charcoal. And although it varies widely from one species to another, and even between clones, 0.558 $g.cm^{-3}$ is considered a representative average of six eucalyptus clones studied by Pereira (2012) in her MS degree thesis[3]. This density is equivalent to 0.558 ton of dry wood per cubic meter. Turning this volume of 35 $m^3.ha^{-1}.yr^{-1}$ into mass, this yield is equivalent to 19.53 metric tons of dry wood per hectare, per year. The average gravimetric yield in the transformation of dry wood into charcoal is 33%. Therefore, 19.53 mt of dry wood is equivalent to 6.44 metric tons of charcoal. In short: 35 $m^3.ha^{-1}.yr^{-1}$ = 19.53 mt of dry wood. $ha^{-1}.yr^{-1}$ = 6.44 mt of charcoal.$ha^{-1}.yr^{-1}$. At the rotation age of 7 years, there will be **45.1** mt of charcoal.ha^{-1}.

The production of 1,000 mt of pig iron requires 750 mt of charcoal (includes the fines not inserted into Blast Furnace and sold to the cement industry, around 70 kg/t pig iron), that is, a harvested area of 16.63 ha. The average production of pig iron in Minas Gerais in the last 4 years was 3.66 million tons per year. Thus, 2.745 million tons of charcoal were consumed, for which 60,865 hectares of planted forests were harvested annually. Seven years is the proper rotation age of a forest for charcoal production. Therefore, maintaining the forest plantations on a sustainable basis requires an area equivalent to seven times the annual consumption. The production of 3.66 million tons of pig iron on sustainable basis requires a total area of 426,055 hectares of forest plantations, which means for every hectare being harvested there are six hectares growing, capturing CO_2 from the atmosphere, and releasing O_2.

The carbon (as CO_2) and oxygen balance, presented in Figure 6, starting with the eucalypt plantation and the harvested wood and tree branches that are sent to the charcoal making masonry kilns, to produce charcoal and completely combust all the charcoal making fumes (volatile material) utilizing the tree branches and foliage as fuel to guarantee complete combustion. In this way no methane emissions occur in the process of charcoal making. The charcoal is then sent to the Mini Blast Furnace to produce pig iron. The details of these calculations can be seen in reference 9. These data are not an LCA for pig iron production since it does not consider scope 2 and scope 3 and other emissions that can be in the presented system such as diesel emissions from the forest machinery and transportation as well as the plantation other emissions such as N_2O in the possible use of nitrogenated fertilizers. Norgate *et alii*[10], publish a LCA for a similar system where the emissions coming from fuel uses, fertilizer and machinery utilized at the forest plantation and harvesting reaches only 240 kg CO_2/ t of charcoal.

In Figure 6 there are two blocks of C as CO_2 and O_2 data. The sustainability CO_2 fixation and oxygen regeneration are the data that represent all the necessary carbon fixation in the eucalypt plantation, the carbon capture, storage, use and oxygen regeneration system illustrated in Figure 1. This system exports wood and tree branches with foliage to the charcoal making operations. The negative CO_2 in these biomasses are 5,271 kg CO_2/t pi and 12,369 kg of regenerated oxygen per metric t of pi. The high value for the O_2 regeneration is due to all oxygen regenerated from the fixated carbon in the biomasses and soil. In the case of CO_2 only the fraction that goes with the wood and branches are considered. The details of this C and O balance are in reference 9. From this figure, in the carbonization step 409 kg of CO_2 is generated due to tree branches and foliage combustion and 326 kg of O_2/t pi is removed from the atmosphere. Another 1,718 kg CO_2/t pi is emitted due to the complete combustion of all the continuous carbonization volatiles and 1436 kg of O_2/t pi removed from the atmosphere. At the Mini Blast Furnace 2013 kg of CO_2/t pi is emitted and 1,636 kg of O_2 removed from the atmosphere. The net result from wood to one metric ton of pig iron is a negative fixation of 1,130 kg CO_2 and positive oxygen regeneration of almost nine tons (8,951 kg O_2). The additional value of 1,584 kg of CO_2/t pi carbon fixation increase of that plantation when compared with the carbon fixation of the native vegetation that was there before the plantation. Details of this can be seen in reference 9. From Figure 2 the CO_2 oxygen equivalent claimed in reference 5 is 8,952/1.56 =5,738 kg.

The wood utilized for charcoal production represents no more than 30% of the total carbon captured in a planted forest system. While the forest is in its growth phase, branches and foliage fall on the ground where they decompose, are incorporated into the soil and there they remain indefinitely if it is not washed away due to erosion[11]. Fungi and bacteria necessary for the survival of the vegetation manage to incorporate a significant amount of carbon in the soil. In Figure 6, the plantation total CO_2 fixation per ton of pig iron considers the soil and roots carbon in the CO_2 fixated but the amount transferred to use does not go with those fixated carbon but oxygen regenerated does. Therefore, from the 17007 kg CO_2/t pi only 5,271 kg CO_2/t pi is transferred to use.

The actual IPCC regulations for CO_2eq. accountability demand the additionality criteria that the revegetation area existing vegetation carbon stock be considered when a plantation is going to replace it. The new stock of carbon captured coming from the new plantation can be considered only by deducing the one that was there before. Therefore, only the additional carbon above the previously existed one is object of CO_2 fixation. If the new amount is lower the difference from the previously one, then the net result is considered emission. The Cerrado region where the new eucalyptus forests are placed has less total carbon when compared to any new eucalyptus plantations[8].

Figure 6 also shows the mass of wood and branches & foliage used in the carbonization process. The branches & foliage are used to guarantee complete combustion of all the carbonization fumes to eliminate the chance of methane emission. To calculate the CO_2 additionality of 1,584 kg CO_2/t pi of this plantation, shown in Figure 6, go to reference 9.

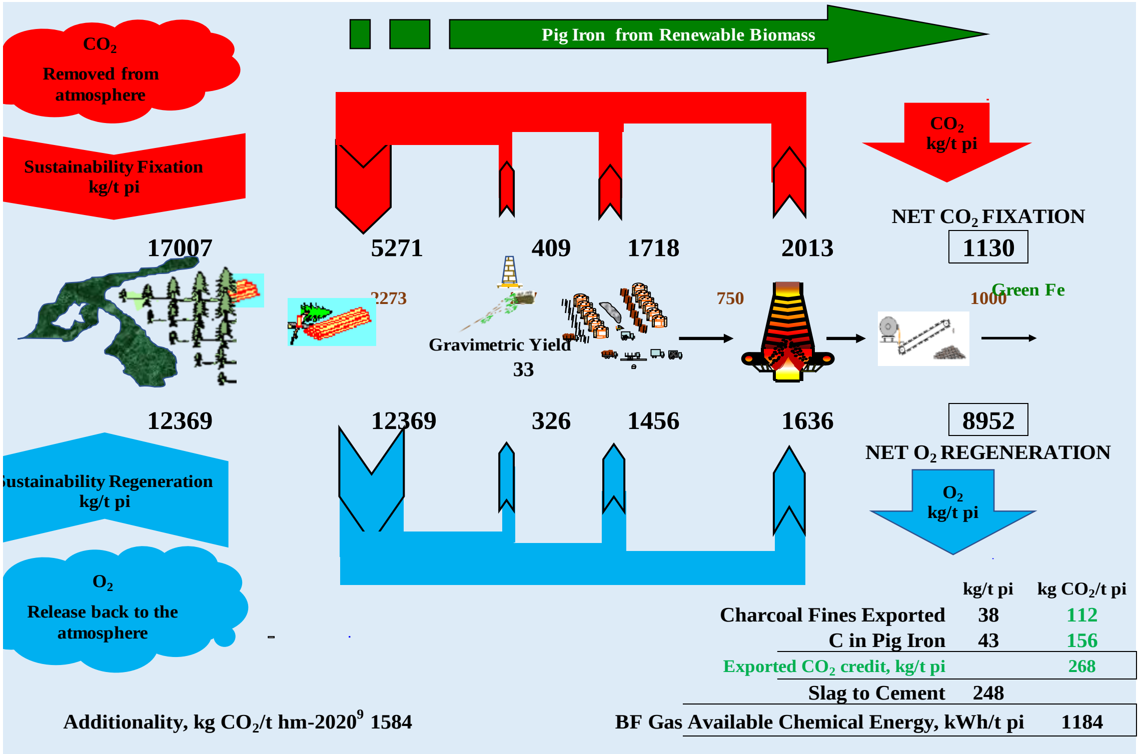

Figure 6- Illustration of the Carbon Capture, Storage & O_2 regeneration natural system to produce primary iron with negative emissions and oxygen regeneration[9].

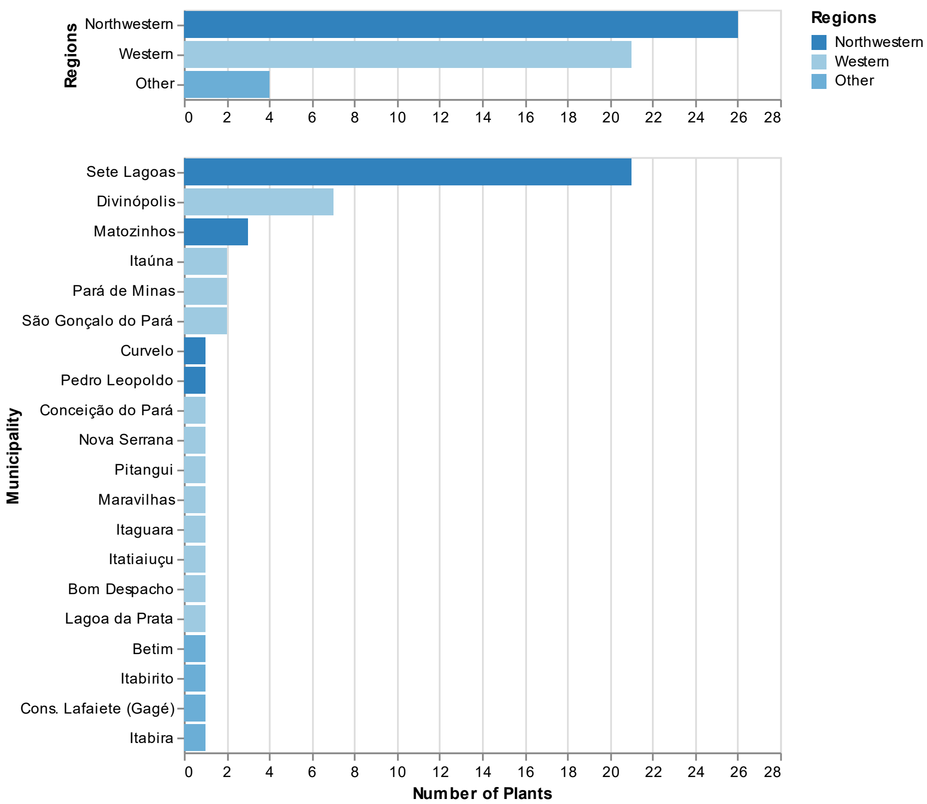

Figure 6. Locations of Minas Gerais merchant pig iron plants.[7]

Figure 6 and Figure 7 show the region and counties in Minas Gerais where small pig iron producers and localized and their estimated capacity, respectively. The majority is near to the iron ore mines. In the last ten years the availability and quality of the lump ore deteriorated, specially by reducing the total iron content of the fines generated. Small charcoal run sinter plants are in operation and the driving force to utilize iron ore pellets increased significantly. Cold bonded pellets are becoming a viable alternative due to its low investment and no need of a traditional fired pellet plants.

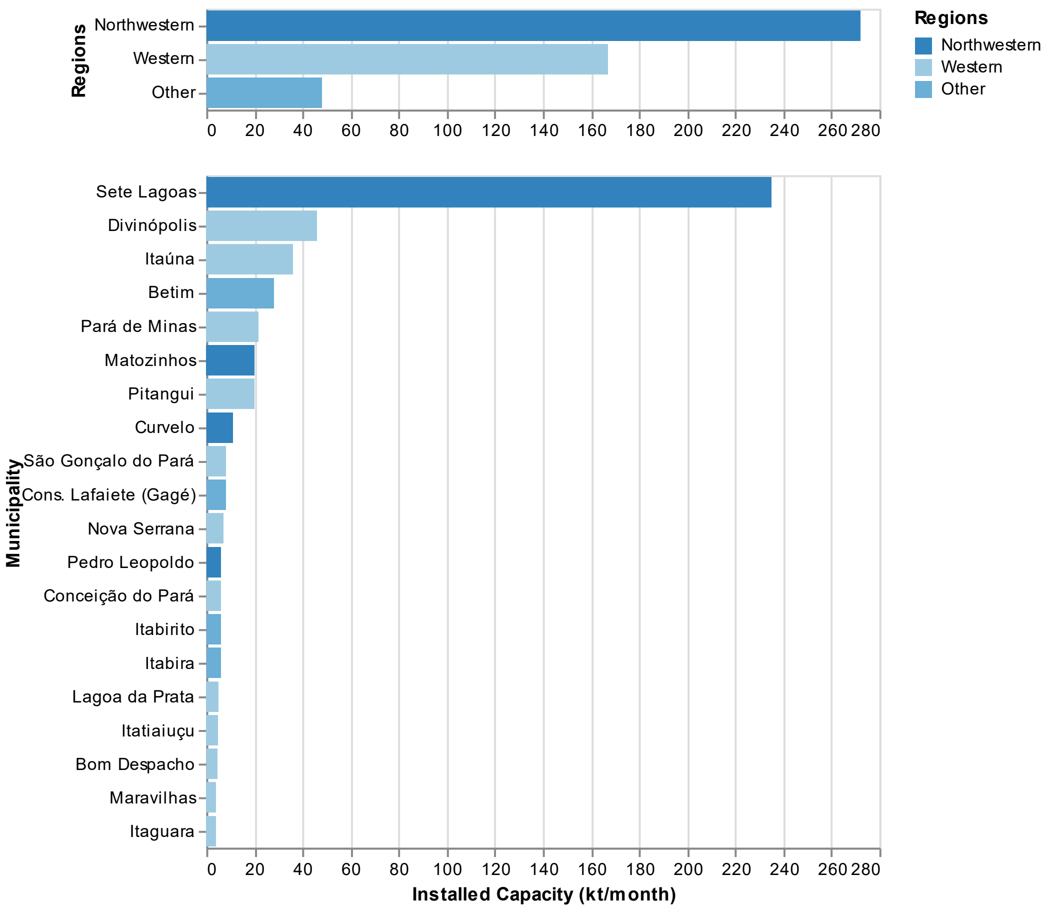

Figure 7. Installed capacity of Minas Gerais merchant pig iron plants; the capacity is in thousands of metric tons.[7]

Conclusions

Photosynthesis is by far the biggest chemical industry on the planet, and it is not likely that there will be a more feasible way to reduce carbon dioxide from the atmosphere and release oxygen. Furthermore, the existence of arboreal vegetation – whether commercial or protective – in a region will bring great additional benefits, among them the reduction of thermal amplitude. This reasoning brings the idea that urban afforestation should be seriously considered as significant part of an extensive forestry program, especially in a tropical country like Brazil. In addition to all the benefits already mentioned, trees will also bring mild climate and well-being to people while walking down a street.

The additional capital investments in land, and expenditures in soil regeneration, forest plantation, native vegetation protection, water basin recovery and maintenance plus a significant new good job generation are expressive costs implied in that cleanest way to produce a metal. Therefore, the oxygen regeneration also promoted in those activities claims to be a fair (mathematically and thermodynamically) consideration of this real and measurable benefit considered in the CO_2 equivalent calculations.

Acknowledgments

The authors acknowledge Mr. Thiago A. de Oliveira for his assistance and discussions on regards to this work.

References

1. *Incentivos Fiscais Concedidos a Empreendimentos Florestais*.; 1966. http://www.planalto.gov.br/ccivil_03/leis/1950-1969/l5106.htm

2. Instituto Brasileiro de Economia (IBRE), Fundação Getúlio Vargas (FGV). *IBA – Annual Report*. Indústria Brasileira de Árvores; 2022. https://www.iba.org/datafiles/publicacoes/relatorios/relatorio-anual-iba2022-compactado.pdf

3. Pereira BLC. *Wood Quality of Eucalyptus for Charcoal Production*. Universidade Federal de Viçosa; 2012. https://locus.ufv.br//handle/123456789/3101

4. Instituto Estadual de Florestas - IEF. Published 2022. http://www.ief.mg.gov.br/

5. Sampaio RS, Assis AN, de Oliveira TA. Atmospheric Profit & Loss — Oxygen Depletion as the Remaining Piece for a Proper CO_2 Emissions Assessment. *Carbon Capture Science & Technology*. 2022;2:100032. doi:10.1016/j.ccst.2022.100032

6. Siderurgia Sustentável. Produção Sustentável de Carvão Vegetal – Sistema Fornos-Fornalha: Manual de Operação. Published online 2019. https://www.undp.org/sites/g/files/zskgke326/files/migration/br/c95597811905d3f965dc363cc589a9e9b3f47d50f710108f0d611de44fe2605a.pdf

7. Sindicato da Indústria do Ferro no Estado de Minas Gerais. *Statistical Yearbook*. SINDIFER; 2021. http://sindifer.com.br/sndfr/anuario-estatistico/

8. Sampaio RS, Resende MEA, de Freitas GD, Branco MAC, Althoff P. Pig Iron from Mannesmann Brazil – Metallic with CO_2 Fixation Credit: An Environmental Favorable Solution for the New Millenium. In: ; 1999.

9. Sampaio RS, de Oliveira TA. Decarbonization Based on Sustainable Biomass in Iron, Steel, and Ferrous Alloys Making: a Continuous Improvement of a Centenary Experience in Brazil. In: Vol Steel Decarbonization. ; 2023.

10. Norgate T, Haque N, Somerville M, Jahanshahi S. The Greenhouse Gas Footprint of Charcoal Production and of Some Applications in Steelmaking. Published online March 2011. https://publications.csiro.au/publications

11. Monbiot G. The Secret World Beneath Our Feet Is Mind-Blowing – and the Key to Our Planet’s Future. *The Guardian*. https://www.theguardian.com/environment/2022/may/07/secret-world-beneath-our-feet-mind-blowing-key-to-planets-future. Published May 7, 2022.