AMBIENTE & SOCIEDADE 25 anos años years

SciELO

Climate change review and the CCS technology contribution to the climate mitigation challenges

Israel Lacerda de Araujo [I]
Hirdan Katarina de Medeiros Costa [II]
Zen Makuch [III]

Abstract: The main issue in this century were the increasing greenhouse gases (GHG) emissions after the industrial cycle, and it became international concerns related to climate mitigation challenges. Thus, our focus is to discuss a historical view between climate change diagnosis and how carbon capture and storage (CCS) technology may contribute to mitigate climate change challenges. Our methodology is a literature review of technical and economic questions of CCS and the analysis based on geological data. Results show anthropogenic GHG sources' geological view from chronologic era highlighted how human interaction with the environment climate conditions, and international climate agreements may encourage changes in new legal, institutional, and normative frameworks under jurisdictions and deal with the challenges for implementing CCS technology via soft power. Therefore, we conclude that governments are responsible for arbitrating and establishing the available resources, the interests between the groups, adjusting costs over time to those they will fund.

Keywords: Climate change; mitigation measures; CCS technology; anthropogenic GHG's source.

[I] Universidade de São Paulo, São Paulo, SP, Brasil.

[II] Universidade de São Paulo, São Paulo, SP, Brasil.

[III] Imperial College London, London, UK

São Paulo. Vol. 25, 2022

Original Article

DOI: http://dx.doi.org/10.1590/1809-4422asoc20210036r1vu2022L2OA

Introduction

The changes in climate patterns observed in the recent geological epoch, the Holocene, have been pointed out as potential for negative impacts on health, social well-being, and the economy. Global changes can be observed in accelerating shrinking glacial environment processes, changing coastlines, average ocean temperature, and indirect impacts, considering how it changes biodiversity maintenance conditions (IPCC, 2014).

Human interactions with each other and with the environment have been responsible for abrupt changes at a regional scale, for example, those observed in lacustrine and fluvial environments (CHIN, BEACH, et al., 2017, PORINCHU, HASKETT, et al., 2017, SCHMIDT, GONZALEZ, et al., 2018). The increasing Greenhouse Gas (GHG) emissions after the industrial cycle are pointed out as the primary cause vector, and it has become the subject of international negotiations in which several countries have committed to the climate mitigation challenge.

The carbon capture and storage (CCS) technology has been elected as a critical component to be adopted in the climate solutions, mainly for a given group of industries due to the CCS resilience of rapidly reducing current levels without significant negative impact on those economic activities the group of industries is involved (IEA, 2013, 2019, 2020a). This technology can be applied to capture the carbon dioxide currently released into the atmosphere by large-scaled stationary facilities, through the process of remodeling and revamping them, then transporting and injecting the capture GHG gas in the adequate geological formations for the permanent sequestration (IEA, 2013).

However, the assurance of committed countries in reducing their emissions has been difficult to accomplish due to a myriad of factors and actors involved in the decision-making process, such as production chain interactions between various agents or between and them and other sectors, having an unclear distribution of gains, income, costs, and losses in the long-term.

This allocation of responsibilities, benefits, and costs along production chains has been a complex function in societies engaged in climate change policies. They embed exogenous variables for the decision-making of agents who, even high GHG emitters, supply essential goods for society and provide significant well-being gains, despite the lack of emphasis on climate policies.

This paper will discuss a historical view between climate change diagnosis based on geological data and the decision-making process in the face of global warming by countries and discuss the CCS technology contributions and challenges as a crucial tool for climate change challenges in society.

Climate change approach from geologic carbon cycles

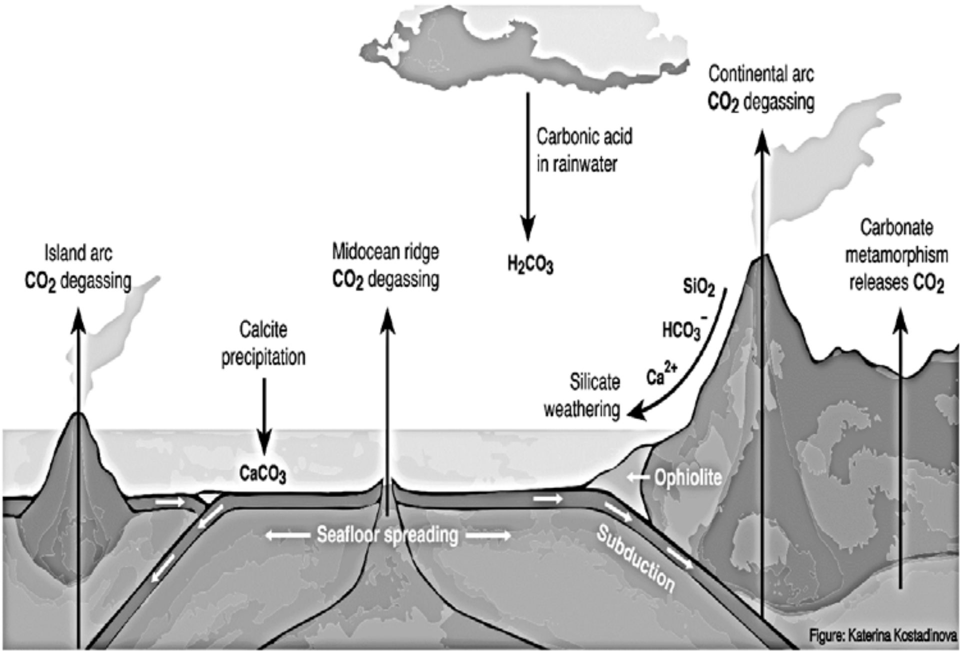
The first consideration to be underlined is how the carbon dioxide enters the atmosphere and the mechanism to remove it back to the crusts, the sea, or the soil.

The carbon flow on shallow layers of the Earth can be represented by mass flow via metamorphic processes, which results in the degassing of the crustal rock under metamorphism and the migration of carbon in the gas form to the atmosphere; by precipitation, in which it migrates from the atmosphere to the continental area and the ocean (ionic form); and by interchange due to the reaction between the seawater and its ocean floor (solid form, such as mineral phases of silicate), and vice versa (BERNER, LASAGA, et al., 1983, CONDIE, 1997). There is also a contribution by tectonic processes and the biological system, being natural sources of carbon exchange with other environments (CONDIE, 1997).

Figure 1 illustrates the carbonate-silicate cycle (known as the inorganic carbon cycle), the elements represented as essential components controlling the carbon dioxide equilibrium system from crustal zone to atmosphere.

The first consideration to be highlighted is how the carbon dioxide leaves the atmosphere and the mechanism to remove it back to the crusts, the sea, or the soil.

Figure 1. Main components of the Earth carbonate-silicate cycle and its sources for the atmosphere system. The Geologic and biologic processes were the most important contributors to the carbon flow



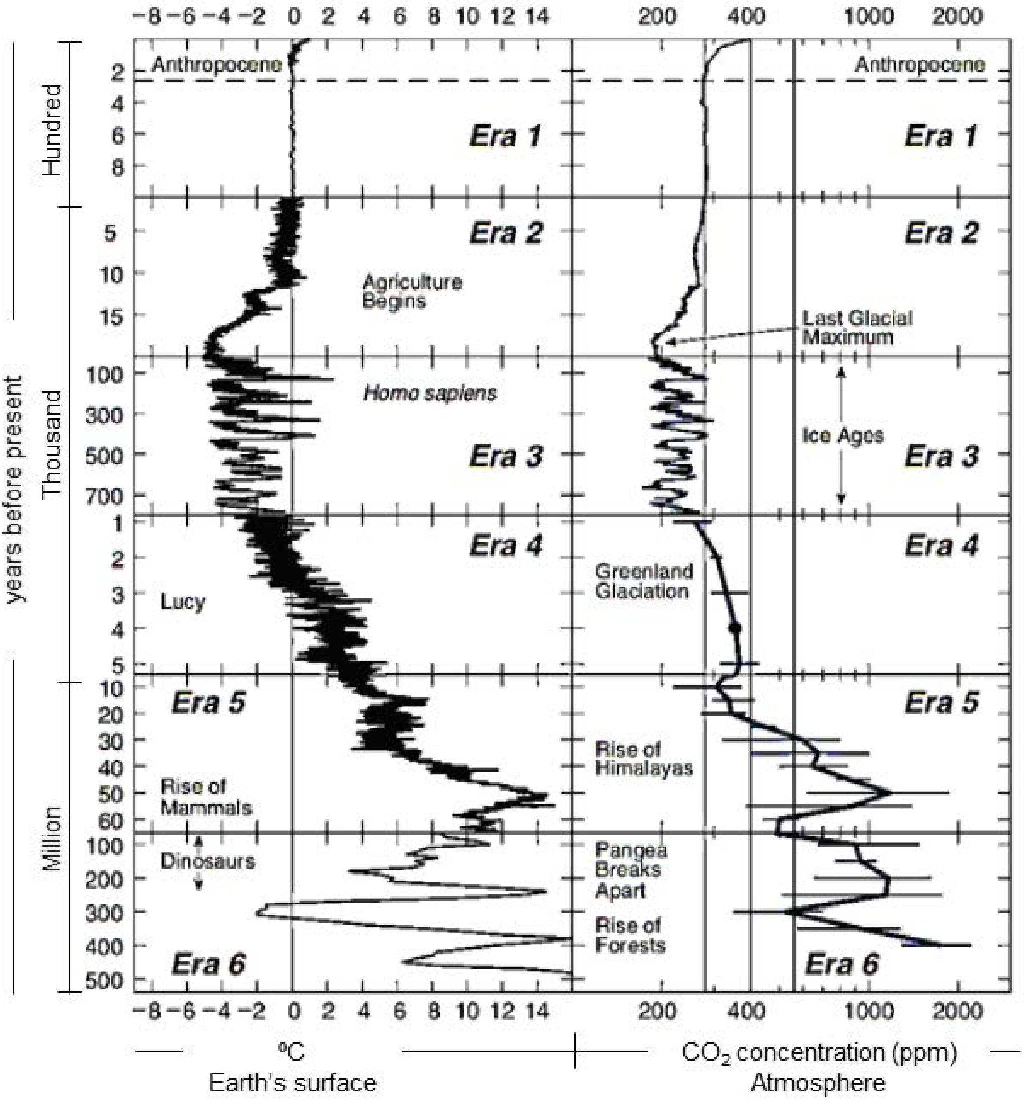
Source: KASTING (2019)

The metamorphic process also contributes to the carbon cycle via the carbonate-silicate reactions or recycling process; the carbon dioxide migrates as H2O.CO2 through the rainwater, in the molecular form of an acid responsible for the weathering process in the long timescale, for the shallow dissolution rocks, including carbonate that insignificant input amount of carbon dioxide in the atmosphere, and, in short-term, for carrying to the ocean carbon and other by weathering by-products that improves carbonate precipitation in the seafloor due to the organic activities, followed by a reworking process and the transport to the subduction zone, leaving the small superficial system (KASTING, 2019).

The volcanism degassing process remained an important natural source of carbon dioxide and other gases to the atmosphere and the ocean. This mechanism could release volcanic gases in the atmosphere by tectonic events through time and inputs directly to the ocean by hydrothermalism in the submarine volcanos (SANTANA-CASIANO, FRAILE-NUEZ, et al., 2016)

Among the natural processes, it can highlight those linked to volcanism, which is pointed out as responsible for the sudden increase in the concentration of carbon dioxide in the atmosphere during the Ypresian, in the Eocene (PEARSON, PALMER, 2000, STOREY, DUNCAN, et al., 2007), and those linked to biological processes, such as the transition to the resurgence of polar glacial formation and its expansion, in the transition to the Oligocene (PEARSON, FOSTER, et al., 2009, SPEELMAN, VAN KEMPEN, et al., 2009). The history of terrestrial climate change over the past 500 million years can be illustrated in Figure 2.

Figure 2. Historical evolution of the Earth's climate. On the left side, the anomalous temperature of the Earth's surface considering average relativity for the 0 ºC equivalent to the preindustrial period's baseline. The right illustrates the carbon dioxide concentration in the atmosphere through the geological era, the critical events that shaped it. Era five represents the Eocene, in which atmospheric carbon dioxide decreases significantly



Source: Salawitch et al. (2017).

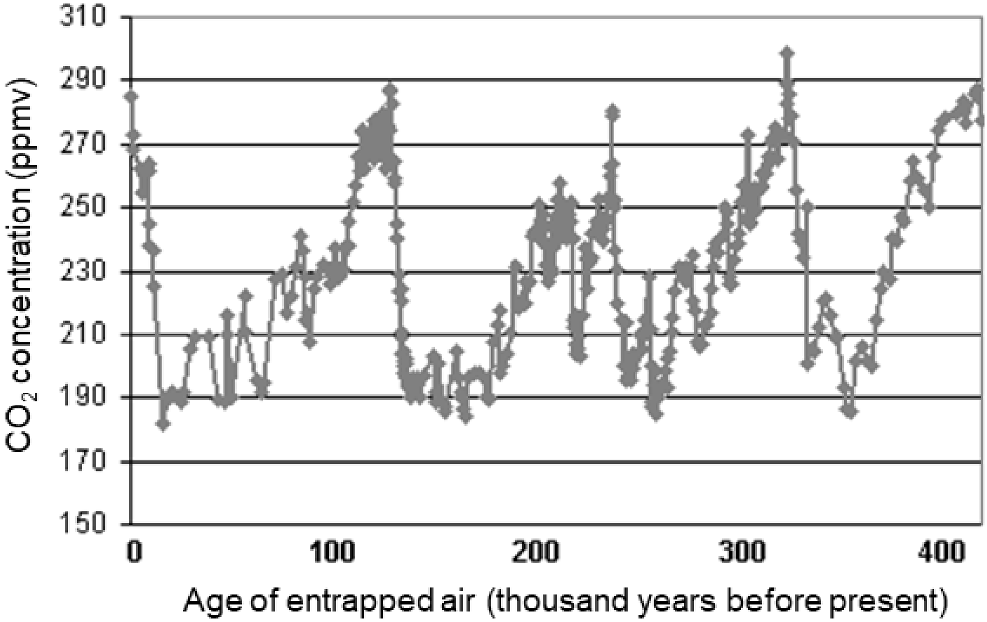
As a system of equilibrium in the long timescale, the carbon cycle would tend to capture molecules from the atmosphere to the ocean and its inert deposits on seafloor via mineral form, through dissolution process, mitigating the effect of carbon dioxide concentration in the atmosphere. In the Anthropocene, however, fossil fuels played a significant role in determining the concentration of carbon dioxide in the atmosphere in a short time, such that systems capable of balancing the exchange system could not absorb the new stock transferred into the atmosphere (CRUTZEN, 2002, PAUL J. CRUTZEN AND EUGENE F. STOERMER, 2000).

The first studies have provided comprehension about the ancient composition of the atmosphere based on geological records, and it impacted the study of climate (BARNOLA et al., 1987).

Analyzing a drilling hole 2,077 meters deep, whose location was the Vostok Glacier in Antarctica, it was interpreted that the concentration of carbon dioxide along the profile sampled was correlated with temperature records. Given the accuracy of the correlation between hole depth and history of atmospheric composition in a complete glacial cycle (BARNOLA et al., 1987, WUNSCH, 2004).

The research was expanded through a new drilling hole, whose maximum depth of 3300 meters was correlated with the age of 420,000 years and 417,000 years respectively for ice and air trapped molecules (ROTHMAN, 2002), and similar data found elsewhere besides the Antarctic continent (DEJI, YAO, et al., 2017, KLEIN, NOLAN, et al., 2016, PETIT, JOUZEL, et al., 1999, THOMPSON, 2000) as well as its correlation with global warming (IPCC, 2006, SEIP, GRØN, et al., 2018, YAMAMOTO, KITAHARA, et al., 2012). Briefly, glacial-interglacial cycles were observed defined at a periodicity of 100,000 years, with carbon dioxide concentration in the atmosphere of up to 300 ppm in a natural glacial cycle (Figure 3).

Figure 3. The Vostok drilling hole's Carbon dioxide concentration, in parts per million in volume (ppmv). The data allows illustrating the last four glacial-interglacial cycles, in which concentration ranged between 190 and 280 ppm of CO_2



Source: https://cdiac.ess-dive.lbl.gov/trends/co2/graphics/vostok.co2.gif. Access: Nov 26th, 2020.

Understanding anthropogenic GHG's source on geological eras

The human-Earth interaction brought about changes in the environment of sufficient relevance for a new division in the geochronological stratigraphic chart to be discussed. Previously, the current time was framed in the Holocene, a time marked from the last glaciation, approximately ten thousand years old, and already under the effect of human interaction and environment, however, with negligible proportion. The agricultural processes by individuals, the increase of the global population, and the consequent urbanization, per se, would motivate the improvement of the time global scale within and beyond the Holocene epoch (ZALASIEWICZ, WATERS, et al., 2017).

Previous research allows inferring the need for a better understanding of the effects of human activity interventions on the environment in both time and space. It has been proposed a subdivision on a geologic time scale based on a markable discontinuity of oxygen isotopes on stalagmites of the Meghalaya cave in India (MARSH, 1864, WALKER, HEAD, et al., 2018), whose point that the cause was a climatic related event with an abrupt change of climate conditions at the beginning of the Holocene, as well as its markers of Greenlandian, Northgrippian and Meghalayan stages/ages – 11.7, 8.2 and 4.2 thousand years, respectively –. Concurrently, the suggestion of including an appropriate geochronologic classification to present-day global changes, which happen faster than usually observed on the global geological cycle, was discussed by academic research; maintain similar scientific criteria in terms of reasonability that surrounded another time scale.

Global Boundary Stratotype Section and Point (GSSP) represents the visual record in a given geological stratum, correlated globally, therefore, without representing only a local or regional change in the conditions of formation and deposition of sediments, and such marker should define a reference point in a geological section and specific locality, called Golden spike (ZALASIEWICZ, WATERS, et al., 2017). Discussions on the recent geological epoch, the Anthropocene, emerged as the period in which the exploitation of natural resources in number and per capita expands in such a way that it modifies future geological records in the form of GSSP and, for instance, indicates a group of climate changes incompatible with natural behavior that will last for the next fifty thousand years (CRUTZEN, 2002, PAUL J. CRUTZEN AND EUGENE F. STOERMER, 2000).

The theme's complexity led to creating the Anthropocene Working Group (AWG) to answer age hierarchy and markers questions. According to the AWG, these discussions[1] include changes in carbon dioxide, methane, and nitrous oxide concentrations in the atmosphere, changes in the isotopic ratio between continental and marine carbon, on physical patterns of the sea, all of them linked to the atmosphere (ZALASIEWICZ, WATERS, et al., 2017).

For the AWG, regardless of the previous effects of human action, only in the middle of the 20th century was the first synchronous and clear marker of the transformative influence of human beings on the main processes, physical, biological, and chemical, on a planetary scale. Preliminary Anthropocene results suggest an Epoch hierarchically positioned after the Holocene, having as a temporal marker the middle of the twentieth century, the plutonium fallout caused by main human activity and affecting albedo in the polar regions (ZALASIEWICZ, WATERS, et al., 2017). Despite plutonium marks proposed by AWG, suggestions for the Anthropocene marker as the end of the 18th century remains latent since it represents the period of increasing global concentration of carbon dioxide and methane in the atmosphere began (CRUTZEN, 2002). The definition of a new geological Epoch remained opened by geoscientists; nonetheless, it is emphasized that the GHG emission growth after the industrial era is directly correlated to human activity, and it might be correlated with a possible new geological epoch.

Since 1950, a virtually exponential increase in key socioeconomic parameters has been observed: population growth has achieved unprecedented levels, as well as

1 - Based on the preliminary recommendation of the AWC, the proposal of a new epoch that will come after the Holocene has been on the analysis by scientists of the International Union of Geological Sciences. Until it is not broadly accepted, the Holocene continuous to be officially the current geological epoch. Informally, the Anthropocene has been used to highlight the diachronous impact of humans on Earth. This paper will take the freedom to adopt the term much more in this informal path.

the levels of urbanization and production necessary for the new demographic profile, such as the significant increase in fertilizer consumption, on energy, on international tourism, on transportation, on telecommunications or even on large dams (STEFFEN, BROADGATE, et al., 2015).

Recent environmental changes on the regional level are also linked to human interaction with the environment.

The climate change' influence on the aquatic ecosystem in the western region of the United States of America has been interpreted by analyzing the Linkins and Grizzly Lakes microfossils, in which the rate and the magnitude of fauna renewal observed in the early 20th century exceeded those observed in the older samples, resulted from the organic production increasing due to warming process (PORINCHU, HASKETT, et al., 2017).

The land-use changes and occupation may lead to relevant river modifications. Studying sedimentary load contained in twenty river courses in western China, it has been observed that the proportion of cultivated land was directly proportional to the increasing in contemporary sedimentary load compared to the sedimentary load generated (SCHMIDT, GONZALEZ, et al., 2018).

Similarly, there is a wide possibility of diagnosis regarding human-induced environmental changes, which allow changes on acceleration tendency of human action effects on the environment (CHIN, BEACH, et al., 2017, STEFFEN, BROADGATE, et al., 2015).

Given the diagnoses, climate issues began to occupy the governmental agenda. By resuming the global warming theme as a focal point, it is possible to understand the emergence of the appeal for mitigating measures. After the beginning of the industrial period, the concentration of carbon dioxide in the atmosphere increased approximately 50%, reaching 420 parts per million (ppm) of carbon dioxide in the atmosphere, significantly increased in the last two decades. Human activity is among the most significant contemporary challenges to be confronted, engaging agents to look for technologies that allow the reduction of carbon dioxide emissions levels in the atmosphere, the changes in production and consumption patterns to achieve a global scaled low-carbon economy(IPCC, 2014).

The CCS technology is one of the eligible mechanisms to solve the GHG effect of anthropogenic origin. As part of the climate change solution, this technology has been targeted within a portfolio to reduce carbon dioxide emissions from fossil fuels and the hard-to-reduce industries (EUROPEAN ENVIRONMENT AGENCY, 2011, IEA, 2011, 2013, 2019).

However, the complex paths between the conceptual CCS application and the concrete implementation of economic production chains and its global effects intersectoral, observing how the CCS can affect the other economic chains, remains as a decisive barrier.

The contribution of the CCS Technology to tackle climate change mitigation challenge

The GHG emissions can be combined into two segments: natural and anthropogenic. The natural emissions include all processes related to biological activity, native vegetation, and natural processes of burning, reforestation, and decomposition of biomass counting diagenetic and metamorphic processes on geologic formations (CONDIE, 1997, IPCC, 2014). The anthropogenic emissions cover those resulting from human activity, especially the burning of hydrocarbons, those linked to agriculture, forests, land-use changes, and industrial processes.

Within anthropogenic sources, GHG emissions can occur immobile over time, such as thermopower plants, large industrial clusters of chemical, petrochemical, refining and fertilizer manufacture, cement and steel industry, which represents a punctual and local concentration of high emission level. They are named stationary sources (MCQUEEN, WOODALL, et al., 2020, MILLAR, ALLEN, 2020).

Another situation can be characterized by the severe difficulty of reducing their emissions, migrating to a low carbon economy and being resilient to the significant changes in their behavior, such as operational thermopower plants, industry, and transport sectors.

The industry and the energy sector can be directly qualified in both criteria, stationary and hard-to-reduce their carbon footprint. Both sources can be classified, directly or indirectly, as challenging to decarbonize and stationary, and emissions linked to them have been of complex resolution only through international climate agreements.

From the 21st Conference of the Parties (COP) agreement – The Paris Agreement –, the need to promote the concept of incentive mechanisms for each economic segment emerged, particularly for large-scale stationary sources without the institutional capacity to adopt appropriate climate change behavior unless external gain factors allow dealing with decarbonizing long-term costs.

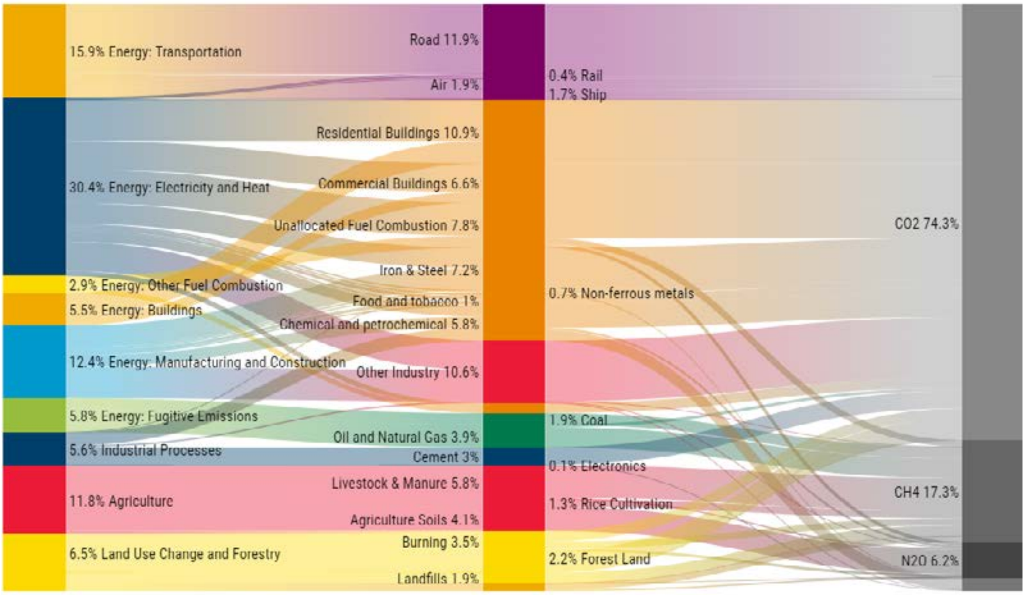
The dimension can be understood from the global view. In 2016, the annual emissions total was approximately 49.04 GtCO2eq, being 33.1 GtCO2eq from the energy and industrial sectors distributed in several end-use sectors (UNCC, 2019), as shown in Figure 4.

There is the coupling of emissions by source and sector on the left side, which could be inferred as part of the link upstream of the production chain, intertwined with the other, for example, energy and transport. On the right, the graph shows emissions by productive activity or final use, which allows us to infer being downstream of the production chain.

As a corollary, agreements that seek to modify the energy sector cause a spreading effect of improving the other end-use sectors. Besides, interventions in end-use sectors may affect the carbon footprint for final consumers, who would be, in elastic interpretation, the main impacted and responsible for emissions, from the final product's point of view.

Hard-to-abate sectors, like steel, cement, dispatchable thermopower plants, longdistance transport, naval, and aviation added up together approximately 27% of AFOLU[2], as shown in Figure 5, it fits the criteria of complex decarbonization emissions factories (DAVIS, LEWIS, et al., 2018).

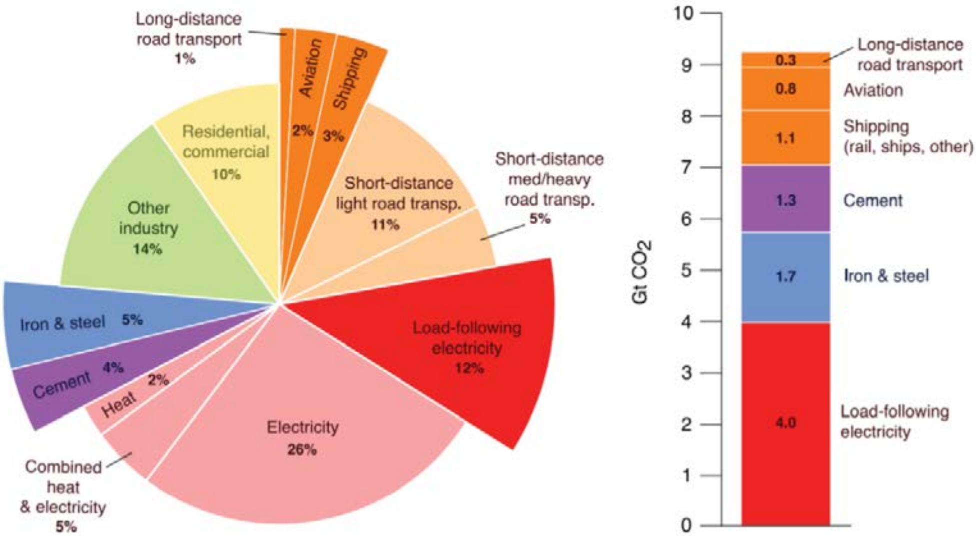
Figure 4. Stacking graph and the correlation between emissions by source sector (left) and end-uses (right)



Source: HERZOG(2009)

2 - AFOLU: Agriculture, Forestry, and Other Land Use

Figure 5. Percentage distribution of GHG emissions. The featured plots (red, orange, blue, and purple) refer to the sectors based on final use resilient to decarbonization. The solution for mitigation in the current context includes direct CCS application in the factories and compensation via natural sinks or BECSS[3]



Source: (DAVIS, LEWIS, et al., 2018).

In terms of cost, solutions are applied to make use of energy efficiency mechanisms, increase productivity on power generation segment and industrial processes, and replace polluting fuels for cleaner options, such as the exchange of thermal coal for natural gas (IEA, 2017, PEE, PINNER, et al., 2018).

For ambitious targets set by developed countries, for instance, net-zero emissions in the European Union and the United Kingdom, intervention is needed to capture GHG emissions before reaching the atmosphere and its geological sequestration. CCS as a critical technology could contribute up to 14% of the total reduction of carbon dioxide emissions in the reference 2060' scenarios, and whose the majority contribution is the ability to allow capture process in the large-scale stationary sources economically feasible (IEA, 2019, 2020b, a).

However, it is essential to adapt the legal and institutional rules to encourage their development in these segments to implement the CCS technology. The absence of incentives probably may discourage an economy with low levels of carbon emissions.

In addition to the definition of a specific legal framework, it is necessary to adapt the network of governance, coordination, and cooperation between countries to understand acceptable practices in the conduct of operations and business necessary in the creation

3 - BECCS: Bioenergy with carbon capture and storage

of the scalability of the CCS projects (ALLINSON, BURT, et al., 2017, IEA, 2017)

Therefore, international climate agreements can lead to aprioritically change in the behavior of decision-makers via soft power (FALKNER, 2016).

Subsequently, they are encouraged to make changes in the new legal, institutional, and normative frameworks under their jurisdictions, intending to implement long-term guidelines that support the reach of a low-carbon economy.

Through the behavior' changing of the various agents along with the production and consumption chain, based on incentives and punishments aimed at reducing the general and unitary costs for society, and that pursues the equitable sharing of duties, in addition to the tax and credit capacity of the countries (Parties) signatories to the international treaty, and in a harmonious way between the present and the future generations (FALKNER, 2016).

Conclusions

Pioneering studies on the effects of human activity on the Earth's climate, especially when compared to rapid growth after the industrial period to the same atmosphere, has raised political concerns about climate change caused by the increase in GHG in the Anthropocene and whose cumulative trajectory may become irreversible due to the importance of economic activities dependent on the energy sector(BARNOLA et al., 1987, IDSO, 1988, SEIP, GRØN, et al., 2018).

From these discussions in society, several countries engaged and made decisions to reduce such emissions.

The form of embodiment took place through the international agreements, highlighting the most relevant, the Paris Agreement. However, they have not been effective in limiting emissions in this case. The complexity occurs because the issuing sources are incomparable directly, given that the costs involved, the maturity of the CCS projects, the accessibility of financial resources to modify the business's trajectory as usual, over and above the contractual, juridic and institutional frameworks involved.

The complexity, as mentioned earlier, could be the case of those sectors whose reduction or cessation of GHG emissions in an economical and efficient method and whose current choice of reductions by country rather than sectoral targets tends to make a choice incomplete or even tricky to achieve global terms.

Once the governments deal with hard-to-abate sectors into mature and complex production chains, the business groups try to bargain with public agents involved to postpone the solutions available.

For that, organized groups with well-defined and firm interests have been characterized by the concentration of benefits on producers and the partition of costs between the whole society, whose conflict interest with the political body on a short term, and a residual uncertainty about the climate issue and make possible only political consensus on an incomplete solution. An urgent need emerged to establish regulation and economic incentives that adequately available resources, territorial realities, and limitations of existing national and international institutions on climate change. For them, the solution that proves feasible involves adopting carbon sequestration via the CCS technology, directly in their stationary sources of GHG emissions or through the BECCS as a compensation mechanism when the technical or economic impossibility of performing it directly at the issuing source.

Governments, therefore, are responsible for establishing suitable institutional rules and for arbitrating the available resources, the interests between the groups, adjusting costs overtime to those they will fund, and, as a result, deal with the problem of the long temporal gap between the cause (emissions) and the consequence (global warming).

Acknowledgements

The authors gratefully acknowledge the support of the RCGI – Research Centre for Greenhouse Gas Innovation, hosted by the University of São Paulo (USP) and sponsored by FAPESP – São Paulo Research Foundation (2014/50279-4 and 2020/15230-5) and Shell Brazil, and the strategic importance of the support given by ANP (Brazil's National Oil, Natural Gas and Biofuels Agency) through the R&D levy regulation, for the resources that made this study feasible; and to the University of São Paulo, on behalf of the Faculty of Economics and the Energy and Environment Institute, for the opportunities for the exchange of knowledge that made it possible to collect data and information for elaboration. We thank the support from the National Agency for Petroleum, Natural Gas and Biofuels Human Resources Program (PRH-ANP), funded by resources from the investment of oil companies qualified in the RD&I clauses from ANP Resolution number nº 50/2015 (PRH 33.1 – Related to Call Nº 1/2018/PRH-ANP; Grant FINEP/FUSP/USP Ref. 0443/19).

References

Allinson, Ken et al. 2017. "Best Practice for Transitioning from Carbon Dioxide (CO2) Enhanced Oil Recovery EOR to CO2 Storage." In Energy Procedia,

Barnola, J.M., Y.S. Korotrevitch, and C. Lorius. 1987. "Vostok Ice Core: A 160, 000 Years Record of Atmospheric CO2." Nature, 329, p. 408-414.

Berner, R. A., A. C. Lasaga, and R. M. Garrels. 1983. "The Carbonate-Silicate Geochemical Cycle and Its Effect on Atmospheric Carbon Dioxide over the Past 100 Million Years." American Journal of Science 283(7): 641–83.

Chin, Anne, Timothy Beach, Sheryl Luzzadder-Beach, and William D. Solecki. 2017. "Challenges of the 'Anthropocene.'" Anthropocene 20: 1–3.

Condie, Kent C. (New Mexico Institute of Mining and Technology). 1997. Plate Tectonics and Crustal Evolution Plate Tectonics and Crustal Evolution. 4o Edition. Socorro, New Mexico.

Crutzen, Paul J. 2002. “Geology of Mankind.” Nature 415(6867): 23.

Davis, Steven J. et al. 2018. “Net-Zero Emissions Energy Systems.” Science 360(6396).

Deji et al. 2017. “Warming and Wetting Climate during Last Century Revealed by an Ice Core in Northwest Tibetan Plateau.” Palaeogeography, Palaeoclimatology, Palaeoecology 487(September): 270–77. http://dx.doi.org/10.1016/j.palaeo.2017.09.009.

European Environment Agency. 2011. 34 COM A Roadmap for Moving to a Competitive Low Carbon Economy in 2050. http://ec.europa.eu/clima/documentation/roadmap/docs/com_2011_112_en.pdf.

Falkner, Robert. 2016. “The Paris Agreement and the New Logic of International Climate Politics.” International Affairs 92(5): 1107–25.

Herzog, Timothy. 2009. “World Greenhouse Gas Emissions in 2005 | World Resources Institute.” WRI Working Paper. World Resources Institute: 2005–9. http://www.wri.org/publication/world--greenhouse-gas-emissions-2005.

Idso, Sherwood B. 1988. “Carbon Dioxide and Climate in the Vostok Ice Core.” Atmospheric Environment (1967) 22(10): 2341–42.

IEA. 2011. SpringerReference Energy Technology Roadmaps.

———. 2013. IEA, PARIS Technology Roadmap Carbon Capture and Storage - 2013 Edition.

———. 2017. IEA Energy Technology Perspectives 2017. PARIS. https://webstore.iea.org/download/summary/237?fileName=English-ETP-2017-ES.pdf.

———. 2019. Transforming Industry through CCUS Transforming Industry through CCUS.

———. 2020a. Energy Technology Perspectives 2020 - Special Report on Carbon Capture Utilisation and Storage Energy Technology Perspectives 2020 - Special Report on Carbon Capture Utilisation and Storage. Paris. https://www.iea.org/reports/ccus-in-clean-energy-transitions.

———. 2020b. World Energy Outlook 2020. https://www.iea.org/reports/world-energy-outlook-2020.

IPCC. 2006. 114 Ipcc Guidelines for National Greenhouse Gas Inventories. Elsevier. https://ci.nii.ac.jp/naid/110004000227.

———. 2014. Intergovernmental Panel on Climate Change. Climate Change 2014 Mitigation of Climate Change Climate Change 2014 Mitigation of Climate Change.

Kasting, James F. 2019. “The Goldilocks Planet? How Silicate Weathering Maintains Earth ‘Just Right.’” Elements 15(4): 235–40.

Klein, E. S. et al. 2016. "McCall Glacier Record of Arctic Climate Change: Interpreting a Northern Alaska Ice Core with Regional Water Isotopes." Quaternary Science Reviews 131: 274–84. http://dx.doi.org/10.1016/j.quascirev.2015.07.030.

Marsh, George Perkins. 1864. Man and Nature or, Physical Geography as Modified by Human Action. NEW YORK: NEW YORK: CHARLES SCRIBNER & CO., No. 654 BROADWAY. 1807.

McQueen, Noah, Caleb M. Woodall, Peter Psarras, and Jennifer Wilcox. 2020. 2020-Janua RSC Energy and Environment Series Chapter 11: CCS in the Iron and Steel Industry.

Millar, R. J., and M. R. Allen. 2020. "Chapter 2: Understanding the Role of CCS Deployment in Meeting Ambitious Climate Goals." RSC Energy and Environment Series 2020-Janua(26): 8–35.

Paul J. Crutzen and Eugene F. Stoermer. 2000. "The Anthropocene." Global Change Newsletter, Global Change Newsletter (41): 239–46.

Pearson, Paul N., Gavin L. Foster, and Bridget S. Wade. 2009. "Atmospheric Carbon Dioxide through the Eocene-Oligocene Climate Transition." Nature 461(7267): 1110–13.

Pearson, Paul N., and Martin R. Palmer. 2000. "Atmospheric Carbon Dioxide Concentrations over the Past 60 Million Years." Nature 406(6797): 695–99.

Pee, Arnout de et al. 2018. "Decarbonization of Industrial Sectors: The next Frontier." McKinsey & Company (June): 68. https://www.mckinsey.com/~/media/McKinsey/Business Functions/Sustainability and Resource Productivity/Our Insights/How industry can move toward a low carbon future/Decarbonization-of-industrial-sectors-The-next-frontier.ashx.

Petit, J. R. et al. 1999. "Climate and Atmospheric History of the Past 420,000 Years from the Vostok Ice Core, Antarctica The Recent Completion of Drilling at Vostok Station in East." Nature 399: 429–36. www.nature.com.

Porinchu, D. F., D. R. Haskett, and S. A. Reinemann. 2017. "Biostratigraphic Evidence of Human Modification of High Elevation Aquatic Ecosystems in the Intermountain West of the United States." Anthropocene 20: 37–47. https://doi.org/10.1016/j.ancene.2017.08.003.

Rothman, Daniel H. 2002. "Atmospheric Carbon Dioxide Levels for the Last 500 Million Years." Proceedings of the National Academy of Sciences of the United States of America 99(7): 4167–71.

Salawitch, Ross J. et al. 2017. Paris Climate Agreement: Beacon of Hope. http://link.springer.com/10.1007/978-3-319-46939-3.

Santana-Casiano, J. M. et al. 2016. "Significant Discharge of CO 2 from Hydrothermalism Associated with the Submarine Volcano of El Hierro Island." Scientific Reports 6(April): 1–9.

Schmidt, Amanda H. et al. 2018. "Agricultural Land Use Doubled Sediment Loads in Western China's Rivers." Anthropocene 21: 95–106. https://doi.org/10.1016/j.ancene.2017.10.002.

Seip, Knut L., Øyvind Grøn, and Hui Wang. 2018. "Carbon Dioxide Precedes Temperature Change during Short-Term Pauses in Multi-Millennial Palaeoclimate Records." Palaeogeography, Palaeoclimatology, Palaeoecology 506(June): 101–11. https://doi.org/10.1016/j.palaeo.2018.06.021.

Speelman, E. N. et al. 2009. "The Eocene Arctic Azolla Bloom: Environmental Conditions, Productivity and Carbon Drawdown." Geobiology.

Steffen, Will et al. 2015. "The Trajectory of the Anthropocene: The Great Acceleration." Anthropocene Review 2(1): 81–98.

Storey, Michael, Robert A. Duncan, and Carl C. Swisher. 2007. "Paleocene-Eocene Thermal Maximum and the Opening of the Northeast Atlantic." Science 316(5824): 587–89. https://www.sciencemag.org/lookup/doi/10.1126/science.1135274.

Thompson, Lonnie G. 2000. "Ice Core Evidence for Climate Change in the Tropics: Implications for Our Future." Quaternary Science Reviews 19(1–5): 19–35.

UNCC. 2019. "Climate Action and Support Trends." United Nations Climate Change Secretariat: 34. https://unfccc.int/sites/default/files/resource/Climate_Action_Support_Trends_2019.pdf.

Walker, Mike et al. 2018. "Formal Ratification of the Subdivision of the Holocene Series/ Epoch (Quaternary System/Period): Two New Global Boundary Stratotype Sections and Points (GSSPs) and Three New Stages/ Subseries." Episodes 41(4): 213–23.

Wunsch, Carl. 2004. "Quantitative Estimate of the Milankovitch-Forced Contribution to Observed Quaternary Climate Change." Quaternary Science Reviews 23(9–10): 1001–12. https://linkinghub.elsevier.com/retrieve/pii/S0277379104000575.

Yamamoto, Yuuki, Naoki Kitahara, and Makoto Kano. 2012. "Long Memory Effect of Past Climate Change in Vostok Ice Core Records." Thermochimica Acta 532: 41–44. http://dx.doi.org/10.1016/j.tca.2011.11.033.

Zalasiewicz, Jan et al. 2017. "The Working Group on the Anthropocene: Summary of Evidence and Interim Recommendations." Anthropocene 19(August): 55–60.

Israel Lacerda de Araujo

✉ israel@senado.leg.br

ORCiD: https://orcid.org/0000-0002-5323-4666

Submitted on: 09/04/2021
Accepted on: 04/12/2021
2022;25:e00361

Hirdan Katarina de Medeiros Costa

✉ hirdan@usp.br

ORCiD: https://orcid.org/0000-0001-5106-6251

Zen A. Makuch

✉ z.makuch@imperial.ac.uk

AMBIENTE & SOCIEDADE 25 anos años years

SciELO

Mudanças climáticas e a contribuição da tecnologia de CCS para os desafios da mitigação do clima

Israel Lacerda de Araujo
Hirdan Katarina de Medeiros Costa
Zen Makuch

São Paulo. Vol. 25, 2022

Artigo Original

Resumo: O principal desafio recente tem sido o problema das emissões de e gases de efeito estufa (GEE) pós-industrialização, e que se tornou objeto de esforços internacionais no intuito de mitigar os efeitos de mudança climática. Esse trabalho visa discutir o tema principal sob ótica das mudanças geológicas de longo prazo, e como a tecnologia de captura e armazenamento de carbono (CCS) pode contribuir para a resolução do desafio climático global. A metodologia baseia-se em revisão literária do CCS e de dados geológicos. O resultado mostra que a atividade humana quanto à GEE tem sido o vetor da definição do Antropoceno como era geológica, e acarretou preocupações políticas e acordos internacionais do clima, que encorajam aperfeiçoamentos legal, institucional e normativo para lidar com desafios da implementação do CCS. Conclui-se pela responsabilidade do poder público como agente que arbitra regras e estabelece recursos disponíveis, interesses envolvidos e ajustes de custo.

Palavras-chave: Mudança climática, medidas mitigatórias, tecnologia de CCS, fontes antropogênicas de GEE.

AMBIENTE & SOCIEDADE 25 anos años years

SciELO

El cambio climático y la contribución de la tecnología de CCS a los desafíos de la mitigación del clima

Israel Lacerda de Araujo
Hirdan Katarina de Medeiros Costa
Zen Makuch

São Paulo. Vol. 25, 2022
Artículo original

Resumen: El contemporáneo ha sido enfrentar el aumento de gases de efecto Invernadero (GEI) postindustrial, tema de los esfuerzos internacionales para mitigar efectos del clima. Este trabajo objetiva discutir el tema principal desde la perspectiva de los cambios geológicos a largo plazo, y cómo la tecnología de captura y almacenamiento de carbono (CCS) puede contribuir a resolver el desafío climático. La metodología se basa en una revisión literaria de CCS y datos geológicos. El resultado muestra que la actividad humana en materia de GEI ha sido vector para definir el Antropoceno como una era geológica, y ha generado inquietudes políticas y acuerdos climáticos internacionales, que fomentan mejoras legales, institucionales y normativas para enfrentar los desafíos de implementálo CCS. Concluye con la responsabilidad del poder público como agente que arbitra reglas y establece los recursos disponibles, los intereses involucrados y los ajustes de costos en el tiempo a los empleados remunerados

Palabras-clave: Cambio climático, medidas de mitigación, tecnología CCS, fuentes antropogénicas de gases de efecto invernadero.