DYNA
ISSN: 0012-7353
ISSN: 2346-2183
Universidad Nacional de Colombia

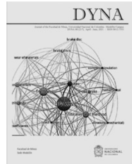
Wechi Benedet, Gabriela; Diederichs Prado, Kárys Cristina; Draeger, Rebecca; Angelkorte, Gerd Brantes; Lins de Mello, André Chame

GHG emissions offset of a combined-cycle natural gas-fired thermopower plant in Northeastern Brazil

DYNA, vol. 88, no. 217, 2021, April-June, pp. 200-210
Universidad Nacional de Colombia

DOI: https://doi.org/10.15446/dyna.v88n217.93050

DYNA
http://dyna.medellin.unal.edu.co/



UNIVERSIDAD NACIONAL DE COLOMBIA

GHG emissions offset of a combined-cycle natural gas-fired thermopower plant in Northeastern Brazil

Gabriela Wechi Benedet, Kárys Cristina Diederichs Prado, Rebecca Draeger, Gerd Brantes Angelkorte & André Chame Lins de Mello

Energy Planning Program, Graduate School of Engineering, Universidade Federal do Rio de Janeiro, Rio de Janeiro, Brazil. gabriela@ppe.ufrj.br, karysprado@ppe.ufrj.br, rebeccadraeger@ppe.ufrj.br, angelkorte@ppe.ufrj.br, andremello@ppe.ufrj.br

Received: March 2nd, 2021. Received in revised form: April 20th, 2021. Accepted: April 28th, 2021.

Abstract
Anthropogenic greenhouse gas (GHG) emissions have caused unprecedented climate change. Both mitigation and adaptation actions have thus become crucial. The combustion of fossil fuels is the leading cause of GHG emissions. Within this context, this work explores several options to offset GHG emissions from a combined-cycle natural gas-fired thermopower plant by 2050. Termopernambuco, in Northeastern Brazil, provides a case study that can be used as a reference for other projects. Therefore, after making an inventory and designing a scenario up to 2050 of its GHG emissions, mitigation actions and offset options are assessed, including a photovoltaic system, fuel mix options, a CO_2 capture and storage (CCS) facility, and livestock-forest integration systems. Such measures are individually evaluated and bundled in five scenarios. Overall results indicate a wide range of offset costs, with livestock-forest integration systems at the lowest end with 37 USD/tCO_{2e} up to a level of 180 USD/tCO_{2e} for CCS.

Keywords: climate change; greenhouse gases; mitigation; offset; thermopower plant; natural gas.

Neutralidad de emisiones de GEI de una central térmica de ciclo combinado a gas natural al noreste de Brasil

Resumen
Las emisiones antropogénicas de gases de efecto invernadero (GEI) han provocado un cambio climático sin precedentes, haciendo cruciales las acciones de mitigación y adaptación. El uso de combustibles fósiles es su principal causa, así que este trabajo explora varias opciones hacia la neutralidad climática de una central térmica de ciclo combinado a gas natural en 2050. Termopernambuco, al noreste de Brasil, proporciona un estudio de caso que se puede utilizar como referencia para otros proyectos. Primero, se realizan el inventario y estimativas de emisiones de GEI hasta el año 2050. Luego, se evalúan las opciones de mitigación y compensación, incluyendo: un sistema fotovoltaico; mezclas de combustibles; captura y almacenamiento de CO_2 (CAC); y la integración de sistemas silvopastoriles. Las medidas son analizadas individualmente y agrupadas en cinco escenarios. Los resultados generales indican un amplio rango de costos de abatimiento, desde 37 USD/tCO_{2e} para sistemas silvopastoriles hasta 180 USD/tCO_{2e} para CAC.

Palabras clave: cambio climático; gases de efecto invernadero; mitigación; compensación; centrales térmicas; gas natural.

1. Introduction

Humanity has negatively influenced the global climate balance, hence provoking great debates about its impact level and the need for actions to manage it better. Organizations of global relevance, such as the Intergovernmental Panel on Climate Change (IPCC), highlight that since the beginning of the pre-industrial era, human behavior has become increasingly harmful to the planet, enhancing the danger over earth temperature [1,2].

As exposed by [1], the levels of anthropogenic greenhouse gas (GHG) emissions in the last three decades are equivalent to the same level of global warming that has occurred in the previous 1,400 years. Moreover, climate

How to cite: Benedet, G.W., Prado, K.C.D., Draeger, R., Angelkorte, G.B. and Mello, A.C.L., GHG emissions offset of a combined-cycle natural gas-fired thermopower plant in Northeastern Brazil.. DYNA, 88(217), pp. 200-210, April - June, 2021.

change has risen the frequency and intensity of extreme events such as droughts, floods, cyclones, hail, and others [3]. This makes it increasingly difficult to predict its destructive magnitudes and potentials, in addition to the respective impacts on society, such as food production and water supply.

According to [1], future low-carbon scenarios require significant interventions in the energy sector, which intensively uses fossil fuels. In this context, there is a current trend of growth in the participation of renewable sources in the global and Brazilian energy matrix. According to the Brazilian decennial planning for energy expansion [4], it is expected that wind and solar sources will jump from a level of 9% and 2% of domestic supply in 2019 to 16% and 8% in 2029, respectively.

With the increased participation of these intermittent sources and the inability to manage the new hydroelectric plants' water flow for expansion, system flexibility represents a challenge for energy supply assurance [4]. Given such circumstances, natural gas thermopower plants are strategically positioned due to their rapid response to activation. This high level of ramp-up makes them critical parts for maintaining the stability of the National Interconnected System and for greater reliability of the Brazilian electrical system [5].

Therefore, natural gas is seen as the energy transition fuel, not only for its lower molecule value than other liquid fuels but also for emitting fewer air pollutants. Although these plants have a lower level of GHG emissions among fossil-fired thermopower plants, their impacts are still significant. Thus, this study aims to analyze possible forms of mitigation and offset for natural gas thermopower plants by developing a case study of Termopernambuco (Termope), a combined-cycle natural gas-fired thermopower plant in operation in Brazilian Northeastern, to propose solutions to neutralize its GHG emissions by 2050.

This paper comprises four sections, including this introduction. Section 2 presents the Materials and Methods applied to evaluate GHG mitigation and offset alternatives. Section 3 presents the Results and Discussions, including the scenarios analyzed. Finally, Section 4 refers to the Conclusion of this study.

2. Materials and methods

Northeastern Brazil is the country's region with the highest growth in power generation by intermittent sources. Thereby, its thermopower plants are essential to ensure continuous demand-supply. Furthermore, among those fueled with natural gas, combined-cycle plants are the ones with the lowest GHG emissions level, although complete start-up takes longer than simple cycle facilities. The mentioned benefit is related to their improved efficiency.

For such reasons, this study was dedicated to assessing the case of Termope since it matches the highlighted environmental and locational aspects of interest. The plant is located at Porto Suape, an industrial port complex in the state of Pernambuco (PE), as seen in Fig. 1. It has 533 MW of installed capacity and its system works through the combined operation of two gas turbines and one steam turbine [6].

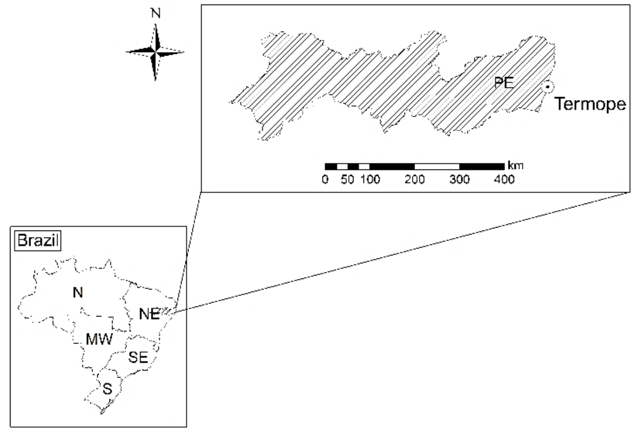


Figure 1. Termope's location.
Source: The authors.

To define options for GHG mitigation or offset, it was first necessary to calculate Termope's emissions according to the adopted methodology. From this step on, potential mitigation and offset measures were assessed for addressing the GHG emissions from gas natural combustion process. After defining the solutions portfolio, the most tangible options were selected for future scenarios formulation, which comprised technology penetration possibilities within a specific time horizon. Such approach represents an important support tool for decision making to achieve the intended climatic management.

This study defined a time horizon based on Termope's expected lifespan, considering that its operation started in 2004 [6]. According to [5], thermopower plants are functional during 20-30 years, which can be extended for 25-30 years more. In this sense, 2050 was assumed as an approximate reference for limiting the scenarios.

2.1. Greenhouse gas emissions

Termope's GHG inventory was based on the year 2019 and developed by IPCC Tier 3 methodology [7]. To achieve this, specific data regarding the power plant and its location were used.

The natural gas composition considered in this paper was obtained from [8], which is the company responsible for gas supply in the region. For calculation purposes, this study applied the technical specifications of General Electric (GE) 7F.04 gas turbines made publicly available by the manufacturer [9]. This classification includes equipment also known by former names, including 7FA.03 turbines, which are mentioned in a report for investors of Neoenergia as the ones used at Termope [10].

2.2. Greenhouse gas mitigation options

According to [1], mitigation refers to actions directed to both GHG sources reduction and sinks reinforcement, which are mechanisms that contribute to atmospheric GHG decrease. In this context, this study considered both strategies. Therefore, varied options were analyzed to reduce GHG emissions from fossil fuel combustion to reduce environmental impacts.

In the case of power plants that meet their self-consumption with their power generation, such as Termope, solar energy may be a mitigation option for supplying part of this demand. It was also considered the possibility of replacing Termope's fuel with biogas or hydrogen mix, in which the first would be a more solid option while the latter could represent a future potential. Also, Carbon Capture and Storage (CCS) was assessed since it is vital to achieving long-term offset targets.

Therefore, this paper proposes a diverse portfolio of mitigation options, which is further detailed in this section.

2.2.1 Photovoltaics

Aiming to reduce emissions related to self-consumption, which currently relies on its own thermopower, this study assessed the implementation of an onsite photovoltaic system for complementing the internal supply-demand. In this context, the authors considered all visually available areas, including rooftops and ground portions. The polygons identification and measurement applied to the Google Earth Pro mapping tool, version 7.3.2.5776.

For system sizing, this paper used version 2018.11.11 of the System Advisor Model (SAM), developed by the National Renewable Energy Laboratory (NREL) under the United States Department of Energy. SAM is a simulation software that allows technical-economic modelling of renewable energy power systems, including photovoltaics. The estimations applied the "Photovoltaic (detailed)" calculation mode through the "LCOE Calculator" option, which provides performance and Levelized Cost of Energy (LCOE) results for specific equipment [11].

Among the equipment available on SAM's database, this study considered the following selection criteria: array configuration technical requirements for maximizing area exploitation, such as nominal power and voltage; well-known manufacturers. Thus, the selected references were: Canadian Solar Inc. CS6U-330P module, with 17,57% of efficiency and 330 Wdc of nominal power; SMA America SC250U (480V) inverter, with 250 kWac of nominal power and 96,8% of electric current conversion efficiency [11].

SAM's database was also used for solar resource estimation by selecting the specific plant location. Thereby, the irradiance data applied refers to a point centered on its largest building. The calculation considered default values of alternate and direct current losses, and disregarded shading parameters. Other information concerning system configuration relied on adaptations from [12], such as: module azimuth, ground coverage ratio (related to tilt and distancing) and direct to alternate current ratio.

Regarding economic-financial parameters, inflation and the exchange rate between Brazilian Reais (BRL - R$) and American Dollars (USD - US$) corresponded to those on Focus Report, the market report issued by [13]. Additionally, this study considered the fixed Weighted Average Cost of Capital (WACC) of Brazilian power generation [14] as a proxy for the discount rate. As for capital and operational costs of photovoltaic technology, the estimations applied adapted data from [15], responsible for subsidizing Brazil's energy planning through official studies.

Then, for comparing the estimated photovoltaic output with the equivalent portion of thermopower consumption to be replaced, 2019's self-consumption was estimated based on Termope's most recent public data. In this sense, it was assumed the exact relation between self-consumption and power generation informed by [16]. Finally, for estimating the Marginal Abatement Cost (MAC), the plant's capital costs were considered already covered, so the photovoltaic LCOE was directly compared with the plant's Variable Unit Cost (VUC) by calculating their gap per mitigated emissions.

2.2.2 Fuel mix

To effectively reduce GHG emissions from burning natural gas, alternative combustion sources were studied by the combination of cleaner and chemically compatible fuels.

The first alternative assessed was biogas originated in landfills. Every year, solid urban waste generation continues to increase in Brazil and worldwide, and its inadequate disposal has negative impacts on the environment and public health. Therefore, the use of biogas resulting from the decomposition of these residues appears as a relevant alternative. Beyond adding value to those, it can incorporate revenue by obtaining carbon credits and electricity generation.

Biogas is a gas with low calorific value when compared to other combustible gases. In the case of Termope, it could be used in the secondary boiler or, in small proportions, combined with natural gas to feed the turbine. As it is a poor gas and presents different impurities, it is necessary to assess the composition of landfill biogas and adapt the equipment to not compromise their structure or impair the plant's efficiency. It is key, however, to achieve a balanced trade-off between emissions reduction and efficiency required. To proceed with biogas use, landfills within the Termope's region have been mapped, among which the closest ones are located at distances between 40-50 km.

The second alternative of fuel mix analyzed corresponds to the use of synthesis gas through biomass gasification, a technology known as a Biomass Integrated Gasification Combined-Cycle (BIGCC). Although it has not yet reached a high technological maturity, it is a promising technology because of its strong potential of environmental performance, reducing emissions of CO_2, SO_x, NO_x and particulate materials [17]. In addition to the advantage of being a carbon-neutral fuel, its use in BIGCC systems with CCS offers the possibility of generating energy with a negative CO_2 balance [18]. Thus, for using this alternative, regional supply availability was analyzed.

The third alternative refers to hydrogen gas (H_2), since it is a potential fuel for a decarbonized future when generated from renewable sources. However, it is necessary to overcome significant technical and economic barriers [19]. For using hydrogen gas in a potential combination with natural gas to supply the plant's demand, some considerations were made for the analysis. To avoid significant changes in the structure of a natural gas-fired thermopower plant, the amount of injectable hydrogen gas in the mixed fuel is limited according to the equipment specifications, varying in volumetric percentage up to 12% [20]. This study considered a 10% volumetric hydrogen ratio in relation to natural gas.

For dimensioning this alternative, energy and water requirements of the electrolysis process to produce 10% in volumetric percentage of H_2 were calculated according to the average monthly consumption of natural gas at the plant. PEM electrolyser was established as the technology for producing H_2, as it is the most suitable when powered by an intermittent source, such as wind or solar. For this purpose, the electric energy required by the electrolysis was estimated by the equipment's efficiency [21], according to eq. (1).

$$Elt = \frac{(PCI \times ProdH_2)}{\eta} \quad (1)$$

Where, *Elt*: energy required by the electrolyser (kWh); *PCI*: hydrogen lower heating value (kWh/kg); $ProdH_2$: H_2 production (kg); η: electrolysis efficiency.

It was adopted 3 kWh/Hm³ for hydrogen lower heating value and 60% for the efficiency of electrolysis process by PEM, according to [22]. As for water consumption, according to [23], it was estimated that approximately 9 liters of water would be needed to produce 1 kg of hydrogen by the electrolysis process.

The electrolysis plant values presented in [23] was used to estimate investment cost. In this sense, the prices related to the renewable plant energy - necessary to feed the system - were not considered, and neither the prices related to the H_2 gas transport and storage.

Finally, the MAC of this measure was estimated, assuming a lifespan of 20 years for the electrolysis plant and an approximate discount rate by the fixed WACC of Brazilian electric power generation [14].

2.2.3 Carbon capture and storage

Carbon capture and storage represents an important mitigation option to deal with climate change. It is one of the few technical solutions capable of capturing up to 90% of CO_2 emissions produced by the use of fossil fuels in electricity generation and industrial processes. Although CCS technology has a great potential to drop greenhouse gases emissions in the long term, it still faces economic and technological barriers [24,25].

A post-combustion system is the most recommended method for CO_2 capture in a thermopower plant already in operation, such as Termope, since it can be add-on to the power plant. Therefore, this route is easier to be implemented in existing plants and provides a better potential for short-term applications. CO_2 is captured in the exhaust from the combustion process, subsequently, the gas is absorbed by an adequate solvent. Thus, the CO_2 is compressed and transported by pipelines to appropriate geological formations for storage [26].

The Oil & Gas sector is one of the pioneers of developing and implementing CCS projects, using the captured CO_2 for enhanced oil recovery (EOR) [27]. CO_2 injection assists in increasing the formation pressure, directing the oil to producing wells. Depending on reservoir parameters, CO_2 blends with the oil into a single-phase at miscible conditions, improving oil mobility and allowing easier flow through the formation [28,29].

The Northeastern Brazilian oil basins only correspond to 7% of oil production in the country and are mainly composed of mature fields and shallow reservoirs, being attractive to EOR implementation and representing an option for lower injection cost due to its lower formations' depth [30,31].

The first stage of the technical feasibility analysis consisted of selecting onshore and mature oil fields that benefit from receiving CO_2 injection from Potiguar, Recôncavo and Sergipe-Alagoas (Northeastern Brazilian) basins, or at least those that were not rejected on the data analysis. Thus, the Executive Summary of Development Plan was used to verify some reservoir characteristics, such as porosity and permeability, original oil in place (OOIP), and oil API degree [32].

This study only considered the miscible CO_2 injection since it provides a greater oil recovery [33]. Typical values of favorable characteristics for the CO_2-EOR application are shown in [34]. These parameters are required but not sufficient for a reservoir to be appropriate to use CO_2 injection. However, some data are not available for public consultation in most of the fields analyzed in this study, thus parameters such as temperature, pressure and reservoir depth, and oil viscosity were not considered. Concerning the depth parameter, shallower reservoirs can be selected as long as they do not contain drinking water in their proximity. The reservoir formation must have a good seal to prevent CO_2 contamination in adjacent formations [34]. Oil fields that do not have OOIP information were discarded.

Using the collected data of oil fields suitable for receiving CO_2 injection, the storage capacity of each field was calculated. Subsequently, the total quantity of CO_2 that Northeastern oil fields can store was estimated. This analysis was based on the methodology adopted by [35], which considers that CO_2-EOR can provide an increase of 10% of the original oil in place in current oil production [33].

Additionally, the storage capacity is related to the ratio between the mass of CO_2 stored per unit mass of oil produced. According to [33], the storage efficiency of the Recôncavo basin corresponds to 0.18 tCO_2/bbl. Since this study was based on the same region of this basin, the same value of storage efficiency was adopted. Using °API data from each of the selected oil fields, the median density was calculated and presented 848.1 kg/m³. These values correspond to a storage of 1.33 tCO_2 per tonne of oil produced. Thus, eq. (2) was used to estimate the oil fields' storage capacity given by the sum of the individual capacity of each field [35]. The results are presented in Section 3.2.3.

$$\sum_{i}^{n} Q_{CO_{2i}} = p \times OOIP_i \times \frac{mCO_2}{mOil} \quad (2)$$

Where, QCO_{2i}: CO_2 storage capacity of the field *i* in million metric tonnes; *p*: percentage of the OOIP that can be additionally produce using CO_2-EOR in %; $OOIP_i$: original oil in place of the field *i* in million metric tonnes; $mCO_2/mOil$: ratio of mass of CO_2 stored per unit mass of oil produced.

Afterward, hotspots were defined for each of the three basins mentioned above, which means that the field with the most significant storage capacity in each basin was considered the delivery point of CO_2. Using a georeferencing tool, the distance between the hotspots and the thermopower plant was calculated to estimate the pipeline length.

Finally, a cost analysis of the CCS technology implementation in the thermopower plant was made using the IECM tool, version 11.2 [36]. This model estimates the costs of implementing the CO_2 capture plant, and the pipeline construction costs. The EOR costs were not considered in this study, as it would not be attributed to the thermopower plant but to the operator responsible for the oil fields.

2.3. Greenhouse gas offset options

The state of Pernambuco is one of the Brazilian states with high levels of soil degradation. According to data from [37], this state has about 63 million hectares of degraded area, representing approximately 7% of its entire territory.

Thereby, it is opportune to intensify local livestock, which has local productivity levels of about 0.9 livestock animal unit per hectare [37], to open new areas to produce planted forests for GHG offset through plant vegetative growth. The Integration Crop-Livestock-Forest (ICLF) agricultural production system was chosen to recover pasture, improve livestock and forestry management, and increase agricultural productivity.

The ICLF system stands out in Brazil as an alternative of integration between different types of production systems with high productivity, cultivation, succession, or rotation to provide a mutual benefit between crops and creations, besides presenting great concern with the recovery of degraded areas. The ICLF aims to develop more sustainable agriculture pursuing a symbiosis between livestock and crops to improve the physical-chemical structure of degraded soils, enhance local biodiversity, and assist in carbon capture by planting planted or native forests [38]. Altogether there are four distinct types of ICLF systems, which are: Integration Crop-Forest (ICF); Integration Livestock-Forest (ILF); Integration Crop-Livestock (ICL); and Integration Crop-Livestock-Forest (ICLF) [39].

Due to the great potential and suitability of the region for bovine production, this study selected the ILF type system due to the low level of mechanization of Pernambuco's crop and the low number of workers with a high level of specialization for mechanized work in the field that a complete ICLF type system would require.

Surveys were done on the main agricultural products that can be developed to implement ILF in the region. Regional suitability for implementing beef cattle was observed due to the lower water necessity than dairy cattle and the cultivation of forests planted with eucalyptus.

Therefore, it was necessary to survey the costs, inputs, productivity, and carbon capture rates of the ILF system of the Brazilian Northeastern region. Cost data linked to this type of production system developed by [40] were used, making adjustments so that the initial investment of these processes would be higher than in the monoculture system as exposed by [41,42]. To collect data from the agricultural supplies needed for this production system [40-43] were used as reference. In turn, to obtain the average yields for the studied region, data from [38,40-46] were used. Finally, to determine the carbon capture rates of the ILF system, data from [43-44,47] were applied.

Table 1.
Termope's GHG mitigation/offset scenarios.

Scenario	Potential for GHG Offset in 2050 (% p.y.)	Description
CCS (C)	100	Total mitigation of Termope's GHGs through CCS
ILF (A)	100	Total offset of Termope's GHGs through ILF
75A+ 25(C+P+H)	100	Offset of 75% of Termope's GHGs through ILF and 25% through mitigation with CCS, photovoltaic system (P) and addition of H2 (H)
50A+ 50(C+P+H)	100	Offset of 50% of Termope's GHGs through ILF and 50% through mitigation with CCS photovoltaic system (P) and addition of H2 (H)
25A+ 75(C+P+H)	100	Offset of 25% of Termope's GHGs through ILF and 75% through mitigation with CCS photovoltaic system (P) and addition of H2 (H)

Source: The authors.

Furthermore, it was defined as a premise that the minimum development time of planted forests should be 25 years. This assumption was made to ensure the accurate capture and storage of carbon removed from the atmosphere in the form of wood rather than being transformed into cellulose or advanced electricity/fuels.

2.4. Scenarios

Scenario analysis provides a way to consider different future possibilities in a long-term horizon, considering uncertainties and examining the requirements for a transition toward a given goal. Its purpose is to provide support for decision makers concerning the future consequences of decisions taken in the present [48].

To achieve the goal of neutralizing the Termope's GHG emissions by 2050, it was proposed to apply the scenario analysis methodology. These scenarios aimed to represent options for penetrating the different GHG mitigation and offset measures previously presented in this study. Thus, five different scenarios were developed (Table 1).

Subsequently, assessments were made on the possibility of developing each type of GHG mitigation/offset measure and its implementation horizons.

3. Results and discussion

This section is dedicated to presenting the results obtained from the application of the methodology described above. In this sense, the grouping structure was maintained, first showing the technical and financial results of each proposed measure, and then relating them to the scenarios.

3.1. Termope's greenhouse gas emissions

From the combustion of natural gas, it was estimated that for each kilogram (kg) of natural gas burned, 2.657 kg of CO_2 were generated.

For the configuration of two 7F.04 turbines, in combined-cycle with a third steam turbine, it was obtained that for each kWh generated, 357 g of CO_2 were emitted. Knowing the total energy generated by Termope in 2019, according to the National Electric System Operator (acronym in Portuguese - ONS), it was estimated that the total GHG emitted in that year was 1.24 Mt of CO_2. As a result, the natural gas consumption corresponded to 466 kton or 597.4 MNm^3.

3.2. Termope's greenhouse gas mitigation

3.2.1 Photovoltaics

The model developed with the SAM tool considered a total land area of 25,042 m^2, enabling the consolidation of a 2.84 MW photovoltaic power system. Its composition included 8,586 modules and nine inverters by the specifications previously mentioned.

The simulation results indicated a capacity factor of 20% and an average annual output of 4,963 MWh, considering the first year of operation as a reference. Such energy amount represented around 8% of Termope's self-consumption. In terms of GHG, the mitigation potential corresponded to 1,491 $tCO2_e$/year, accounting for 0.14% of the total emissions estimated by this study for 2019.

The capital and operation costs obtained for the proposed system were, respectively, 3.1 MUS$ and 13,835 US$/year. After levelizing these figures to the present value, the resulting LCOE was 0.05 US$/kWh. Therefore, the calculated MAC for this mitigation option was 48.10 US$/$tCO_{2e}$.year.

Although its contribution may seem of minor importance, this was considered an appropriate option since this kind of system has a short-term implementation of approximately one year [15]. Furthermore, this solution may serve as a good practice reference, encouraging the dissemination of similar projects within corporations. Hence, this is a measure capable of collaborating with renewable energy expansion and climate change mitigation.

3.2.2 Fuel Mix

For fuel mix alternatives, the feasibility of each option was verified. In the case of landfill biogas, it was observed that the regional generation capacity is much lower than the plant's fuel demand. Also, biogas production related to the decomposition of organic matter from urban solid waste decreases considerably over the years, reducing supply throughout the landfill lifespan. Therefore, the use of this type of fuel does not represent a feasible alternative, mainly due to its lack of availability in the long run.

For the second alternative, the BIGCC use analysis, a deficit of biomass was observed in the region. According to [49], Pernambuco presents the worst biomass supply performance among the states in the Northeast region, with demand almost seven times greater than the legal supply. Due to the lack of supply, using a combined-cycle with integrated biomass gasification was discarded as an option.

Regarding the use of hydrogen gas, calculations of energy and water consumption were performed so that a volumetric proportion of 10% H_2 was met. Using as a reference the volume of gas, for a monthly average of approximately 50 Mm^3 of natural gas, 5 Mm^3 of H_2 is required. According to the calculation parameters mentioned in Section 2, the electricity required by the electrolysis was estimated at 24,892 MWh/month, and the consumption of approximately 4 million liters of water per month is also required. With these requirements, an electrolyser of approximately 35 MWe is needed.

It was assumed that the entry of such technology might occur up to 2030, with an estimated capital cost of 52.5 MUS$ this year. The implementation of this technology could allow a 9.8% emission reduction, and with this, the obtained MAC for this measure was 41.46 US$/$tCO_{2e}$.year.

3.2.3 Carbon capture and storage

Considering 381 Brazilian oil fields in production, of which 219 are onshore and in Northeastern Brazil, 90 were selected in the scope of this study as they are reasonable to receive CO_2 injection. These fields' total estimated storage capacity was 143 $MtCO_2$, considering a stock of 1.33 tCO_2 per ton of oil produced (Table 2).

Using a georeferencing tool, the fields that presented the greater storage capacity from each basin were selected as hotspots for this study: Canto do Amaro, from Potiguar Basin, Água Grande, from Recôncavo Basin, and Pilar, from Sergipe-Alagoas Basin. Fig. 2 shows the locations of Termope and the hotspots. The distance between Termope and Canto do Amaro field is 438 km, and between Termope and Pilar and Água Grande fields is 557 km. Then, it was established the construction of only one pipeline, due to the large-scale gains of this type of construction [50].

Potiguar Basin presented an estimated storage capacity of 39.4 $MtCO_2$, Recôncavo Basin demonstrated a storage capacity of 91.8 $MtCO_2$, and Sergipe-Alagoas Basin indicated a capacity of 11.9 $MtCO_2$. Hence, only the pipeline's construction connecting Termope to Pilar and Água Grande fields would be necessary since these fields can provide a storage capacity of 103.7 $MtCO_2$, providing sufficient storage volume to mitigate Termope's emissions in the long term. Supposing the volume of CO_{2e} emissions provoked by Termope, the chosen pipeline would afford a lifetime of approximately 90 years to mitigate the combined-cycle natural gas-fired thermopower plant emissions or even other emission sources located around it.

IECM tool configuration selected amines as a solvent for capturing the CO_2 from Termope. Results showed an Equivalent Annual Cost of 64.95 MUS$/year to implement the capture plant and to build the pipeline, considering a power plant lifetime of 30 years. In this sense, Termope’s LCOE would be increased by US$ 64.90/MWh, while the MAC was estimated at US$ 179.51/tCO_{2e}.year.

Table 2.
Storage capacity for each considered sedimentary basin.

Sedimentary basin	Total of fields	CO_2 storage ($MtCO_2$)
Recôncavo	45	91.8
Potiguar	32	39.4
Sergipe-Alagoas	13	11.9
Total	90	143.1

Source: The authors.

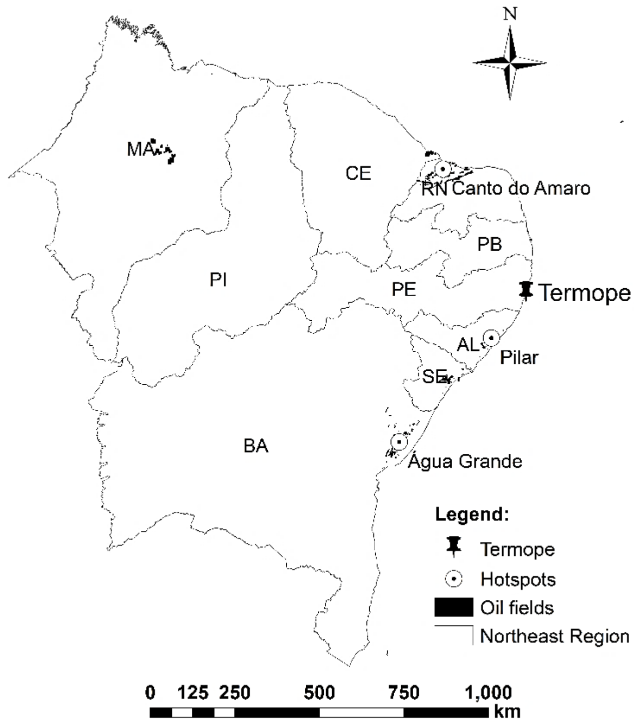


Figure 2. Location of the hotspots fields and Termope.
Source: The authors.

CCS is an incipient technology, and there are no projects on a commercial scale yet, only pilots, thus this mitigation measure has significantly high costs, which tend to decline due to learning by doing [51,52]. However, this alternative is attractive for a carbon-neutral future, as it is one of the only mitigation technologies capable of substantially contributing to the reduction of CO_2 emissions in the long term, whether from energy sources or industrial processes [53,54].

3.3. Offset of Termope's greenhouse gases

The implementation of the ILF system is highly beneficial for both rural and thermopower producers. From Termope's point of view, this agricultural production system comes as a technological solution for GHG offset and as good business practice since this system can align its efforts against climate change. For the rural producer, as it allows the recovery of degraded pasture, this system generates increased productivity of this producer's key production (livestock). It helps in financial stability in the long term. Forest element enters as a type of savings that must be introduced to serve as financial stock when unforeseen events occur in its main production process.

However, it is essential to note that carbon capture and storage during the vegetative growth period is only considered an environmental GHG offset process if the wood of this planted forest is used for nobler purposes than roasting or burning use, as furniture or construction industry use.

Another point is that the forest helps to increase local biodiversity, resulting in more significant amounts of animal species on the property, which helps in pest control and provides less need for chemical pesticides. There is also water bias, in which the forest helps to reduce the consumption of water by livestock due to the improvement of thermal comfort of the animal through shadows and decreases the surface runoff, increasing the permeabilization of water in the soil during intense rains. It should be noted that the ILF is a means of agricultural production that improves soil fertility and mitigates local erosive processes. However, for this to happen, it is necessary to intake large volumes of nitrogen fertilizers, being this system considered a high productivity agricultural production process.

Therefore, high levels of GHG emissions (9.5 tCO_{2e}./ha.year) were estimated. However, this system could become a major GHG mitigator when together with eucalyptus forestry, by stocking CO_2 (30.5 tCO_2/ha.year) in the soil through the root system of the trees and in the woody material of these same trees, reaching average levels of 21 tCO_{2e}/ha.year. With this, an average investment of approximately 36.81 US$/$tCO_{2e}$.year was obtained for the implementation of this type of GHG offset method, using a 773 US$/ha. year.

Hence, it would be necessary to implement this type of production system in about 90,000 hectares up to 2043 so that, by 2050, the planted forests are sufficiently developed to capture high rates of CO_2 during their cell growth. Although this area seems high, it represents only about 0.2% of the entire degraded pasture area of the state of Pernambuco, thus being possible for its implementation in more favorable places.

3.4. Scenarios

According to the most recent edition of the Report of Annual Estimates of Greenhouse Gas Emissions in Brazil [55], emissions related to the energy sector, including power generation, have been growing year by year. In 2015, this sector contributed to more than a quarter of the total emissions in the country, with the largest share due to fossil fuel combustion. Therefore, the increased need to drive thermopower plants to meet growing demand, added to periods of drought that harm hydroelectric generation, contributes in a relevant way so that emissions from this category also increase, especially in cases of absence of mitigation/offset measures and policies to encourage renewable sources expansion.

Regarding Termope's case, the measures described in previous sections aim to minimize net emissions to collaborate, even individually, with the slowdown of the associated impacts. Nevertheless, even if there are local initiatives, they are also in line with the national actions indicated in the Third Biennial Update Report of Brazil to the UNFCCC [56]. Among them, it can be highlighted the promotion of photovoltaic systems in centralized and distributed generation, the increased use of biofuels, and the restoration of degraded pastures.

Table 3 summarizes the Marginal Abatement Cost for each option. These costs reflect the amount incurred so that 1 tCO_{2e} is neutralized.

The scenarios for the adoption of mitigation or offset measures by Termope, illustrated in Fig. 3, showed that it is possible to offset Termope's GHG emissions within the

Table 3.
Storage capacity for each considered sedimentary basin

Analyzed Option	MAC (US$/ton CO_{2e})
ILF	36.81
H_2 Fuel Mix	41.46
Photovoltaic	48.1
CCS	179.51

Source: The authors.

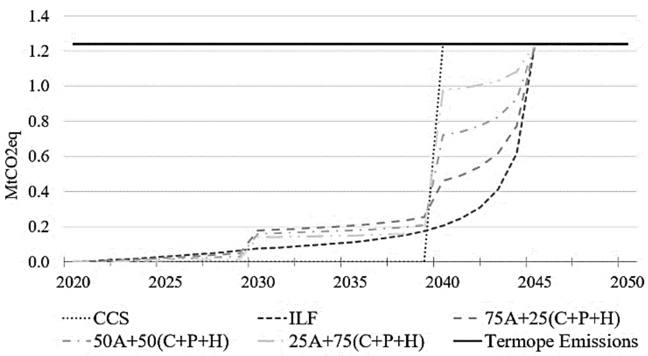


Figure 3. Evolution of mitigated/offset emissions up to 2050.
Source: The authors.

planned horizon. Among the criteria exposed, the photovoltaic system cannot neutralize GHG emissions alone, not due to technological limitations, but because of a lack of available area. However, it is relevant to stimulate similar initiatives in other operational units and to compose combined scenarios.

It should also be observed that the scenarios considered the use of these measures starting in 2030 and 2040, respectively, because hydrogen and CCS are incipient technologies yet. This is justified by their need to achieve technological maturity on a commercial scale. Also, in the case of CCS, both the capture plant and the carboducts will need environmental licensing, leading to time barriers.

On the other hand, scenarios contemplating the ILF option demonstrated a linear horizontal behavior of CO_2 offset of this production system after 2045. This means that from that year on, ILF systems will be able to offset the years for a minimum amount of CO_2 consistent with the value indicated by these horizontal lines. This premise was adopted since ICLF systems present significant interannual volatility, because they depend on climatic factors for their development. This system considers vegetative growth rates of adopted species that follow growth lines with substantial volatility [57].

In financial terms, Fig. 4 shows that among the options capable of annulling the net emissions of Termope's operation, the one composed exclusively of ILF was the most accessible. In this context, as CCS insertion in scenarios increased, the costs also rose progressively. The photovoltaic system and hydrogen costs and their total mitigation capacities were not significant compared to CCS and ILF. However, given the possibility of a portfolio solution, these measures can be considered to corroborate the company's strategic vision and to turn it into a pioneer in its surroundings.

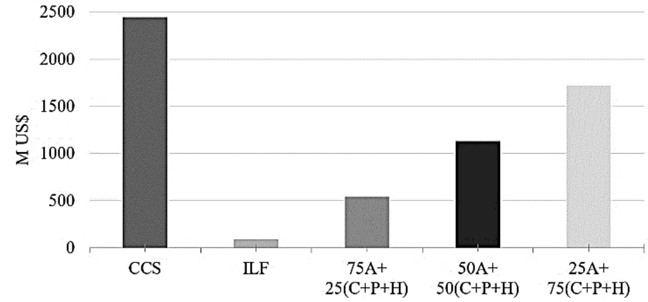


Figure 4. Total mitigation/offset costs, according to proposed scenarios.
Source: The authors.

Thus, the joint analysis of Fig. 3 and Fig. 4 concludes that, strictly from the point of view of costs and the search for the fastest solution among the current possibilities, the ILF scenario would be the most indicated. In contrast, a more diverse scenario would still ensure goal achievement and would be less exposed to the risk of complications in the conduct of any of the measures. Thus, these diversified scenarios would be more favourable, as they would avoid a situation of dependence on an exclusive action.

4. Conclusion

Through the scenarios proposed in this study, it is observed that there are many possible ways to offset GHG emissions from natural gas thermopower plants. Such scenarios are based on technologies already practiced, such as ICLF and photovoltaics, and on technologies still in development, such as hydrogen from renewable sources and CCS. It occurs that ICLF and photovoltaics have lower costs than CCS. The ILF scenario, for example, indicates CO_2 offset costs 96% lower than the CCS scenario, 87.74 MUS$ against 2,445 MUS$.

Hence, the scenarios analysis shows that the ILF option is the most suitable from a financial perspective. In contrast, the CCS scenario is the most expensive, but, once implemented, it would make it possible to substantially capture CO_2 emissions in a quick and accurate way over the long term, facilitating the avoided emissions monitoring. As their main positive point, the diversified scenarios have the fact that they are less exposed to the risk of complications, as they do not depend on one exclusive action, providing greater reliability.

The MAC of ILF, hydrogen, photovoltaics, and CCS, to mitigate a ton of CO_2, are US$ 36.81, US$ 41.46, US$ 48.10, and US$ 179.51, respectively. According to [58], to meet the goals established in the Paris Agreement, the price per ton of carbon should be in the range from 50 to 100 dollars by 2030. With this pricing, ILF, hydrogen and photovoltaics would have a more favorable implementation than the purchase of carbon credits. For CCS, the same cannot be said. CCS MAC would need to fall by at least 56% to be considered economically viable in an optimistic scenario.

Regarding the photovoltaic solution, despite not showing significant results for the Termope's carbon offset due to limited area availability, this measure is valid to reduce a portion of the plant's energy self-consumption. To become a significant option, it would be necessary to use larger areas, but by doing so, the costs may change too. Furthermore, the dissemination of such initiative, considered a good practice, may positively impact stakeholders.

Carbon capture and storage technology proves to be a promising means of carbon offset, but it requires high initial investments. The implementation of CCS initially causes a considerable energy penalty for the thermopower plant, requiring electrical energy consumption from greater volumes of fossil fuel to carry out the CO_2 capture, storage, and transport process. Also, this technology is responsible for greater demands and water consumption, which is not a problem in Termope's case since it already captures seawater. Nevertheless, it ends up causing an energy penalty due to the water desalination process. However, CCS may positively impact energy security in the region due to the possibility of using this captured CO_2 to increase the recovery factor of mature oil and gas wells.

As for ILF systems, in addition to the important role in combating climate change, this measure also has other benefits, such as bringing the company closer to rural producers, qualifying labor and generating jobs, recovering degraded pasture areas, increasing biodiversity, and reducing water consumption by livestock. Notwithstanding, it is necessary to observe the need to implement monitoring, inspection, and control procedures for this type of production. The wood produced should not be used for electricity or biofuels generation purposes but stocked in logs to create furniture and other inputs to store CO_2 for a long time through eucalyptus cell growth.

Regarding the alternatives studied for a possible fuel mix, the first two, landfill gas and synthesis gas processed through biomass gasification, proved to be unfeasible for Termope, mainly due to the lack of available inputs. Thus, only H_2 was considered. However, its implementation depends on several factors such as water availability, water demineralization plant, availability of surplus energy from renewable sources and H_2 storage tanks. In its financial analysis, only the investment values related to the electrolysis plant were considered. Even so, it is understood that this is an alternative that may prove viable for the near future, with the growth of intermittent renewable sources in Northeastern Brazil and technological development in the coming years.

Therefore, the carbon offset of a gas-fired thermopower plant such as Termope requires great logistical challenges. There is not only a single best alternative but diverse possibilities.

In short, the technologies that are already commercially available bring interesting results with lower costs, but demand, for example, greater investments in areas for the installation of photovoltaic modules, which is not often possible, or in qualified labor for carrying out the monitoring of areas for the implementation of agricultural production systems such as the ILF type. Moreover, despite CCS showing results through high monetary investments, literature shows that in the long term it has great importance for maintaining atmospheric CO_2 levels within the expected climatic scenarios of 1.5 and 2.0ºC. It also causes lesser impacts on local water availability since it needs smaller proportions than ILF systems and can be installed close to coastal regions, where it is possible to use seawater.

Additionally, it is important to highlight that the scenarios did not consider the emissions related to life cycle analysis (LCA). This approach, for instance, could provide more assertive and valuable information, possibly leading to the prioritization of different scenarios. According to [59], a coal-fired power plant with 90% CO_2 capture would actually avoid only 72% of emissions, taking into account LCA. However, this assessment was not conducted for Termope's case, so comparability is not guaranteed. Thus, it is recommended for future research.

Acknowledgment

This work is the result of an institutional partnership between COPPE/UFRJ and the Neoenergia Group. The authors declare that no confidential company data was used in the preparation of this paper. The authors would like to thank Neoenergia for providing the conditions for this study, and also CAPES, CNPq and FAPERJ for its financial support, through the granting of master's and doctoral scholarships.

References

[1] IPCC, Climate change 2014: synthesis report. Contribution of working groups I, II and III to the Fifth assessment report of the intergovernmental panel on climate change, Core Writing Team, R.K. Pachauri and L.A. Meyer, eds., IPCC, Geneva, Switzerland, 2014, 151 P.
[2] Rochedo, P.R.R., Development of a global integrated energy model to evaluate the brazilian role in climate change mitigation scenarios, D.S. Thesis, Universidade Federal do Rio de Janeiro, Brazil, 2016.
[3] OCHA (United Nations Office for the Coordination of Humanitarian Affairs), El Niño: Southern Africa faces its worst drought in 35 years, United Nations Office for the Coordination of Humanitarian Affairs, [Online]. 2016. Available at: https://www.unocha.org/story/el-niño-southern-africa-faces-its-worst-drought-35-years.
[4] EPE - Empresa de Pesquisa Energética, Plano decenal de expansão de energia 2029, Brasília, DF, Brazil, 2020.
[5] Tolmasquim, M.T., Energia termelétrica: gás natural, biomassa, carvão, nuclear. Empresa de Pesquisa Energética (EPE), Rio de Janeiro, Brazil, 2016.
[6] Neoenergia, Termopernambuco, Térmica, Grupo Neoenergia, [Online]. 2020. [Accessed: 04-Sep-2020]. Available at: https://www.neoenergia.com/pt-br/sobre-nos/linhas-de-negocios/Paginas/termica.aspx.
[7] IPPC - Intergovernmental Panel on Climate Change, Guidelines for national greenhouse gas inventories, vol. 2(2, Institute for Global Environmental Strategies, Japan, 2006.
[8] Copergás - Companhia Pernambucana de Gás, Produtos, Companhia Pernambucana de Gás, [Online]. 2020. Available at: https://www.copergas.com.br/produtos/. [Accessed: 04-Sep-2020].
[9] GE - General Electric, 7F.04 Gas Turbine | 7FA Turbine | GE Power, General Electric, [Online]. 2020. [Accessed: 04-Sep-2020]. Available at: https://www.ge.com/power/gas/gas-turbines/7f-04.
[10] Neoenergia, ITR: Informações trimestrais, [Online]. 2015. [Accessed: 04-Sep-2020]. Available at: http://www.neoenergia.com.
[11] NREL - National Renewable Energy Laboratory, System Advisor Model (SAM), National Renewable Energy Laboratory, [Online]. 2020. [Accessed: 04-Sep-2020]. Available: https://sam.nrel.gov/.
[12] Aguilar, G.J.R., Metodologia para avaliação do dimensionamento de sistemas fotovoltaicos conectados à rede, MSc. Thesis, Universidade de São Paulo, Escola Politécnica, Brazil, 2018.
[13] BACEN - Banco Central do Brasil, Relatório de Mercado Focus, [Online]. 2019. [Accessed: 04-Sep-2020]. Available at: https://www.bcb.gov.br/content/focus/focus/R20191122.pdf.
[14] ME - Ministério da Economia, Parecer SEI No

30/2019/COGEN/SUENE/SECAP/FAZENDA-ME, Brasília, Brazil, 2019.
[15] EPE - Empresa de Pesquisa Energética, Nota Técnica PR 07/18: Premissas e custos da oferta de energia elétrica no horizonte 2050. Série: Estudos de Longo Prazo, Rio de Janeiro, Brazil, 2018.
[16] Neoenergia, Relatório de Sustentabilidade 2018, Neoenergia. [Online]. 2018, 104 P, [Accessed: 04-Sep-2020]. Available at: http://ri.neoenergia.com/sustentabilidade/relatorios/.
[17] Buratto, W.G., Costa, V.J., Ribeiro, C.B. and Gueri, M.V.D., Análise da co-gaseificação de resíduos de biomassa na Serra Catarinense E avaliação da eficiência ambiental desta tecnologia, Rev. Gestão Sustentabilidade Ambient., 4(December), pp. 473-481, 2015. DOI: 10.19177/rgsa.v4e02015473-481
[18] Hoffmann, B.S., O ciclo combinado com gaseificação integrada e a captura de CO_2: uma solução para mitigar as emissões de CO_2 em termeletricas a carvão em larga escala no curto prazo?, MSc. Thesis, Universidade Federal do Rio de Janeiro, Brasil, 2010.
[19] Abdin, Z., Zafaranloo, A., Rafiee, A., Mérida, W., Lipiński, W. and Khalilpour, K.R., Hydrogen as an energy vector, Renew. Sustain. Energy Rev., 120(May), art, 109620, 2020. DOI: 10.1016/j.rser.2019.109620
[20] de Pinho, L.L.R., Avaliação da produção de hidrogênio a partir de excedentes de energia eólica utilizando algoritmos evolucionários multiobjetivo, MSc. Thesis, Universidade Federal do Rio de Janeiro, Brasil, 2017.
[21] Ursúa, A., Gandía, L.M. and Sanchis, P., Hydrogen production from water electrolysis: current status and future trends, Proc. IEEE, 100(2), pp. 410-426, 2012. DOI: 10.1109/JPROC.2011.2156750
[22] Buttler, A. and Spliethoff, H., Current status of water electrolysis for energy storage, grid balancing and sector coupling via power-to-gas and power-to-liquids: a review, Renew. Sustain. Energy Rev., 82(February) pp. 2440-2454, 2017. DOI: 10.1016/j.rser.2017.09.003
[23] IEA - International Energy Agency, The future of hydrogen: seizing today's opportunities, 2019. DOI: 10.1787/1e0514c4-en
[24] Budinis, S., Krevor, S., Mac Dowell, N., Brandon, N. and Hawkes, A., An assessment of CCS costs, barriers and potential, Energy Strateg. Rev., 22(May), pp. 61-81, 2018. DOI: 10.1016/j.esr.2018.08.003
[25] Rochedo, P.R.R. et al., Carbon capture potential and costs in Brazil, J. Clean. Prod., 131, pp. 280-295, 2016. DOI: 10.1016/j.jclepro.2016.05.033
[26] de Oliveira, C.C.N., Potencial técnico e econômico da aplicação de rotas de captura de carbono em processos industriais Brasileiros, MSc. Thesis, Universidade Federal do Rio de Janeiro, Brazil, 2015.
[27] Ren, B., Ren, S., Zhang, L., Chen, G. and Zhang, H., Monitoring on CO_2 migration in a tight oil reservoir during CCS-EOR in Jilin Oilfield China, Energy, 98, pp. 108-121, 2016. DOI: 10.1016/j.energy.2016.01.028
[28] Gozalpour, F., Ren, S. and Tohidi, B., CO_2 EOR and storage in oil reservoirs, Oil & Gas Science and Technology, 60(3), pp. 537-546, 2005. DOI: 10.2516/ogst:2005036
[29] IEA - International Energy Agency, World Energy Outlook 2018: Highlights, 2018. DOI: 10.1787/weo-2018-2-en
[30] ANP - Agência Nacional do Petróleo Gás Natural e Biocombustíveis, Campos em Declínio de Produção, [Online]. 2017. [Accessed: 07-Sep-2020]. Available at: http://www.anp.gov.br/images/Palestras/campos_maduros_royalties/Tabita_Loureiro.pdf.
[31] Manrique, E. et al., EOR: current status and opportunities, Proc. - SPE Symp. Improv. Oil Recover., 2, pp. 1584-1604, 2010. DOI: 10.2118/130113-ms
[32] ANP - Agência Nacional do Petróleo Gás Natural e Biocombustíveis, Sumários executivos dos planos de desenvolvimento, [Online]. 2020. [Accessed: 07-Sep-2020]. Available at: http://www.anp.gov.br/exploracao-e-producao-de-oleo-e-gas/gestao-de-contratos-de-e-p/fase-de-producao/planos-de-desenvolvimento.
[33] Ravagnani, A.T.F.daS.G., Modelagem técnico-econômica de seqüestro de CO_2 considerando injeção em Campos Maduros, D.S. Thesis, Universidade Estadual de Campinas, Brazil, 2007.
[34] Bachu, S. et al., Final report by the CSLF task force on technical challenges in the conversion of CO_2 -EOR projects to CO_2 Storage projects, Carbon Sequestration Leadership Forum, 2013.
[35] Merschmann, P.R. d.C., Szklo, A. and Schaeffer, R., Technical potential and abatement costs associated with the use of process emissions from sugarcane ethanol distilleries for EOR in offshore fields in Brazil, Int. J. Greenh. Gas Control, 52, pp. 270-292, 2016. DOI: 10.1016/j.ijggc.2016.07.007
[36] NETL - National Energy Technology Laboratory, Integrated environmental control model, [Online]. 2020. [Accessed: 07-Sep-2020]. Available at: https://www.cmu.edu/epp/iecm/index.html.
[37] LAPIG - Laboratório de Processamento de Imagens e Geoprocessamento, Atlas digital das pastagens Brasileiras, [Online]. 2020. [Accessed: 07-Sep-2020]. Available at: https://pastagem.org/index.php/pt-br/tools/atlas-digital-das-pastagens-brasileiras.
[38] Empresa Brasileira de Pesquisa Agropecuária - EMBRAPA, Integração lavoura-pecuária-floresta : o produtor pergunta, a Embrapa responde, Embrapa Ce. Brasília, DF, Brasil, 2015.
[39] Nobre, M.M. and de Oliveira, I.R., Agricultura de baixo carbono: tecnologias e estratégias de implantação. Brasília, DF, Brasil, 2018.
[40] Angelkorte, G.B., Modelagem do setor agropecuário dentro de modelo de análise integrada Brasileiro, MSc. Thesis, Universidade Federal do Rio de Janeiro, Brasil, 2019.
[41] Pedreira, B.C. et al., Integração lavoura-pecuária: novas tendências, Novos sistemas de produção. Lavras, 2017, pp. 128-160.
[42] ILPF - Rede ILPF, Conheça os casos de sucesso de quem aplicou a ILPF em sua propriedade rural, [Online]. 2020. [Accessed: 07-Sep-2020]. Available at: https://www.redeilpf.org.br/quem-ja-usa.
[43] Empresa Brasileira de Pesquisa Agropecuária - EMBRAPA, Pesquisa mostra interferência das árvores na lavoura em sistemas ILPF, [Online]. 2019. [Accessed: 07-Sep-2020]. Available at: https://www.embrapa.br/busca-de-noticias/-/noticia/40579890/pesquisa-mostra-interferencia-das-arvores-na-lavoura-em-sistemas-ilpf.
[44] Salton, J.C. et al., Sistema São Mateus - Sistema de Integração Lavoura-Pecuária para a região do Bolsão Sul-Mato-Grossense, Comunicado Técnico, 186(6), pp. 1-6, 2013.
[45] Oliveira, P.P.A. et al., Balanço e emissões de gases de efeito estufa em sistemas integrados, Palestras: intensificação com sustentabilidade. I Congresso Brasileiro de Sistemas Integrados de Produção Agropecuaria e IV Encontro de Integração Lavoura-Pecuaria no Sul do Brasil, UTFPR Câmpus Pato Branco, 2017.
[46] ILPF - Rede ILPF, ILPF em números, [Online]. 2016. [Accessed: 07-Sep-2020]. Available at: http://www.redeilpf.org.br/arquivos/2016-cpamt-ilpf-em-numeros.pdf.
[47] Sato, J.H. et al., Understanding the relations between soil organic matter fractions and N_2O emissions in a long-term integrated crop-livestock system, Eur. J. Soil Sci., 70(6), pp. 1183-1196, 2019. DOI: 10.1111/ejss.12819
[48] Gallopin, G., Hammond, A., Raskin, P. and Swart, R., Branch points: global scenarios and human choice. A resource paper of the global scenario group. PoleStar Series. 1997, ISSN: 1400-7185
[49] MMA - Ministério do Meio Ambiente, Biomassa para energia no Nordeste: atualidades e perspectivas. Programa das Nações Unidas para o Desenvolvimento - PNUD, Brasília, DF, Brasil, 2018.
[50] da Silva, F.T.F. et al., CO_2 capture in ethanol distilleries in Brazil: Designing the optimum carbon transportation network by integrating hubs, pipelines and trucks, Int. J. Greenh. Gas Control, 71, pp. 168-183, 2018. DOI: 10.1016/j.ijggc.2018.02.018
[51] Manne, A. and Richels, R., The impact of learning-by-doing on the timing and costs of CO_2 abatement, Energy Econ., 26(4), pp. 603-619, 2004. DOI: 10.1016/j.eneco.2004.04.033
[52] IEA, Can CO2-EOR really provide carbon-negative oil?, International Energy Agency, [Online]. 2019. [Accessed: 07-Sep-2020]. Available at: https://www.iea.org/commentaries/can-co2-eor-really-provide-carbon-negative-oil.
[53] Global CCS Institute, The global status of CCS: 2018, Global CCS Institute. 2018, 84 P.
[54] IEA, 20 years of carbon capture and storage: accelerating future deployment, International Energy Agency, 2016. DOI: 10.1787/9789264267800-en
[55] MCTIC - Ministério da Ciência Tecnologia Inovações e Comunicações, Estimativas anuais de emissões de gases de efeito estufa no Brasil, Brasília, DF, Brasil, 2017.
[56] MCTIC - Ministério da Ciência Tecnologia Inovações e Comunicações, Brazil's third biennial update report to the United Nations framework convention on climate change, Brasília, DF, Brazil, 2019.

[57] do Nascimento, F.A.F. et al., Sistema de crescimento e produção para povoamentos de Pinus taeda na região norte de Santa Catarina, Cerne, 21(2), pp. 235-242, 2015. DOI: 10.1590/01047760201521021494
[58] CPLP, Report of the high-level commission on carbon prices, carbon pricing leadership coalition, World Bank Group, 2017. DOI: 10.7916/d8-w2nc-4103
[59] Castelo-Branco, D.A., Avaliação do real potencial de redução das emissões de CO_2 equivalente com uso da captura em uma UTE a Carvão, D.S. Thesis, Universidade Federal do Rio de Janeiro, Brasil, 2012.

G.W. Benedet, completed a BSc. Eng in Civil Engineering in 2011, a MBA in Project Management in 2014, and an MSc. in Renewable Energy and Environment in 2017. She worked at important construction projects in Brazil and abroad. Currently, she is a Dr. candidate in the Energy Planning Program at COPPE/UFRJ, Brazil, mainly interested in subjects such as energy transition, sustainability, change mitigation and integrated assessment models. Her thesis research focuses on the role of innovation in alternative energy transition scenarios.
ORCID: 0000-0002-8840-117X

K.C.D. Prado, is an BSc. Eng. in Environmental Engineer, with specialization in Occupational Safety Engineering from the UFRJ, Brazil. Worked for more than three years in environmental consulting business. Currently, she is a master's student in Energy Planning at COPPE/UFRJ, mainly interested in subjects such as energy transition and sustainability. Her thesis research focuses on the complementarity of power generation sources and the related impacts on energy commercialization.
ORCID: 0000-0003-4547-7139

R. Draeger, is a MSc. student in Energy Planning Program at COPPE/UFRJ. She holds a BSc. Eng. in Petroleum Engineering from UFF in 2017. She worked with Oil & Gas regulation at Brazilian National Agency of Petroleum, Natural Gas and Biofuels (ANP). Her research focuses on improving the modeling of crude oil quality and its representation in the CenergiaLab's in-house global integrated assessment model (COFFEE). Her main research interests are carbon capture and storage, energy transition, integrated assessment models and climate change mitigation.
ORCID: 0000-0003-0897-323X

G.B. Angelkorte, is a Dr. researcher in PPE/COPPE/UFRJ. His dissertation is focused on the modeling of the agricultural sector and land use. He participated in research projects funded by Greenpeace and IDB about agricultural and land use low carbon strategies. He holds a MSc. in Energy Planning (COPPE/UFRJ). In 2019, he defended his Thesis "Modeling of the Agricultural Sector Within a Brazilian Integrated Analysis Model". He holds an BSc. Eng. in Environmental Agricultural Engineer from Fluminense Federal University (UFF) and a Sp. course in Environmental Engineering from Cândido Mendes University.
ORCID: 0000-0003-0385-4565

A.C.L. Mello, completed a BSc. Eng. in Environmental Engineering in 2018, and a Sp. in Environmental Management in 2021. He worked in the electrical sector, with emphasis on environmental management for three years. Currently, he is a master's student in Energy Planning Program at COPPE/UFRJ.
ORCID: 0000-0001-5152-6756