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THE POTENTIAL OF A CO2 STORAGE SYSTEM COUPLED TO A RANKINE ENERGY STORAGE SYSTEM

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Abstract. *This work presents a novel Rankine-based energy storage system coupled to a carbon storage system (CCS). CCS are energy-intensive systems that depend on external sources of electrical energy. We want to demonstrate that the CCS system can be attractive using the stored CO_2 as the working fluid of a Rankine electrical generation system. In this case, a pumping system (from the Rankine cycle) uses surplus electrical power from the grid to compress the CO_2, previously captured, to a high-pressure reservoir. Part of the stored CO_2 returns to the Rankine closed cycle at peak times and high pressure. The high-pressure CO_2 that returns to the Rankine cycle absorbs heat from the CCS power plant (stored in Thermal energy storage tanks), and, finally, the CO_2 passes through turbines to recover part of the stored electrical energy that came from the grid. Applying an energy balance to the overall system, we found out that this coupled CCS-ES system could promote carbon neutrality to the fossil power plant while storing energy with a roundtrip efficiency of 18.8% (with heat waste at 50 ^oC) to 24% (with heat waste at 200 ^oC). Although it is not an energy storage system alone, it proves useful on both fronts: storing carbon in economic reservoirs at high-pressure and making renewable energy sources more dispatchable with energy storage*.
Keywords: *Carbon Storage, Energy Storage, CCS, Heat Waste, CCS-ES*

1. INTRODUCTION

Since the Kyoto Protocol's establishment in the late 90's, studies have been conducted to develop processes that enable the capture and storage of CO2 with focus to minimize greenhouse gas emissions. Especially after the IEA released a roadmap in 2009 (updated in 2013) claiming that the CCS is a critical and essential solution to mitigate greenhouse gas emissions (IEA,2013), tons of papers have been published regarding this topic, especially between 2009 and 2012 (Karimi, 2015). But despite so much research and development, CCS still remains far from the investment agenda and reality. The high energy demand of the CCS process is the greatest reason for this abyss between theory and practice. Therefore, this paper aims to present a novel system, which combines the CCS from a thermal power plant with an energy storage system based on a Rankine Cycle This proposed system has the potential of counterbalancing the high costs of capturing and storing CO2, by using heat waste in the process and delivering stored energy to the grid at peak-time hours.

In order to clarify the relevance of this study in the actual global goal of minimizing greenhouse gas emissions, this paper was divided into the following sections: first, we briefly describe the CCS process and expose some particularities that hamper its actual implementation and present the reasons why CCS still plays a role in the present context. Then, we bring a few data and discussion regarding the barriers we could overcome by using an energy storage system together with the CCS and present the novel proposed system. The following sections then present the methodology, results, discussion, and conclusions.

1.1 The CCS and its obstacles

Carbon capture and storage consists of separating the CO2 from the flue gas emitted by industries or fossil-fired power plants, compressing it, and store it. The final storages are usually geological formations, which may be well isolated from the atmosphere (IPCC, 2005). It is common to use CCUS instead of CCS because of the term "Utilization" added, indicating that part of the captured CO_2 is used in food, plastic, pharmaceutical industries. CO2 utilization, however, is not carried out in a huge range of processes, once the molecule is stable and its transformation requires great amounts of energy (Lau et al., 2021).

The capture of CO2 occurs in basically three different ways: in pre-combustion, post-combustion, and oxyfuel-combustion. The most common in coal- and gas-fired power plants is post-combustion capture.

For post-combustion capture, the most common of the three, the flue gas from the combustion chamber is normally conducted to a packed bed reactor filled with a selective adsorbent material, which adsorbs the CO2. Heat is then used to elevate the temperature and desorb CO2. The pure CO2 is then dehydrated and taken to a tank from where it is compressed and conducted to its final storage, usually a geological formation, where it can be stored as supercritical fluid.

Geological formations are the most common storages for CCS. They are relatively cheap and environmentally acceptable (Carro et al., 2021). It is estimated that the available and adequate geological formation (saline aquifers and gas/oil reservoirs) in the world could store 2 centuries of anthropogenic CO2 emissions (Lau et al.,2021). Another storage is the steel tanks, which are feasible to store up to 3000tons of pressurized CO2 (Carro et al.,2021).

But the CCS involves some issues. Besides the lack of consistent CCS regulations and energy policy, and the issues concerning to find a geological storage that fullfills some requirements, the amount of energy used in the process and the capital investment are high, currently making the CCS an unattractive investment (Sgouridis et al, 2019; Lau et al., 2021)

Although the CCS, per se, is not the answer for reducing emissions – which will be mainly achieved by the transition to renewable energies – it plays an important role in the world climate agenda. IEA (2018) has reasserted that the goal of reducing the emissions to the intended levels - while maintaining this rate of growth in energy demand - will only happen with the effective and extensive capture and storage of carbon. Although the CCS has its issues, it is a significant palliative way to reduce emissions while the world is in the process of migrating to clean energy. Moreover, CO2 as supercritical fluid has been successfully employed in the novel thermodynamic cycles for power generation. As well exposed by Zhu (2017) and Ahn et al. (2015), all this attention to supercritical CO_2 is due to the high efficiency it presents even with mild turbine inlet temperature and to the simple and compact layout and turbomachinery required.

1.2 Combining CCS and Energy Storage

In this section we present a novel system that integrates the process of storing carbon with storing electrical energy. This system intends to make the process of CCS more attractive to the fossil power plant. This system does not intend to solve the problem of high energy consumption of the process of capturing carbon from the flue gas – a subject that has been widely investigated in other studies (Singh et al.,2019; Ahmed et al.,2020; Abuelnoor et al.,2021). On the other hand, this novel system proposes a way to have some counterbalancing gains for the high costs of the CCS. The system we propose integrates the CCS with an energy storage system and is based on a Rankine Cycle and we call it CCS-ES.

What would be the benefits of combining carbon and energy storages, once the CO_2 should be eventually decompressed from its storage and recompressed again? We list below some of the key benefits. 1) It could be used also as an interseasonal energy storage: It is calculated that for cases when 80% or more of the energy supply come from renewables, especially solar, wind and hydro power, inter-seasonal energy storages are required (Mouli-Castillo et al.,2019). It happens because the intermittency of renewables sources does not occur only in short terms as a day duration, but also depends on the seasons; 2) The heat waste of the fossil fueled power plant could be used, even the mild temperature one; 3) Its usefulness lasts more than its lifespan: when the geological formation be finally full of CO_2, it will still work as an energy storage system, but will no longer receive more fluid from CCS.

Let us now introduce the CCS-ES and its operation. The fossil fueled plants feed the grid with electrical power. The flue gas generated in the fossil fueled power plant is processed and the pure CO_2 is captured and pre-stored in a low-pressure tank (LPT) for future compression and storage, in the process known as CCS. The fossil power plant also produces a great amount of heat. The renewables, on the other hand, operate according to the immediate availability of their source and in some periods of time it generates a surplus amount of power.

The system we propose (CCS-ES) operates in two stages: charging and discharging. Instead of using power generated from the fossil power plant, like currently done, the compressor uses surplus energy from the renewable power plants during low-demand periods of time and compresses the fluid to its final storage, the high-pressure tank (HPT). The HPT will normally be a geological formation, but in this study, it was simulated as a rigid tank with conditions near the pressure and temperature of a geological well. This process comprises the charging phase and is shown in Figure 1.

During peak-time hours, the discharging phase takes place. Part of the stored CO_2 is released to pass through the Rankine Cycle: the fluid increases its enthalpy by changing heat with hot water from the fossil power plant; then it passes through the turbine generating power, and returns to the LPT, from where it will be recompressed and stored again. Figure 2 shows the discharging process.

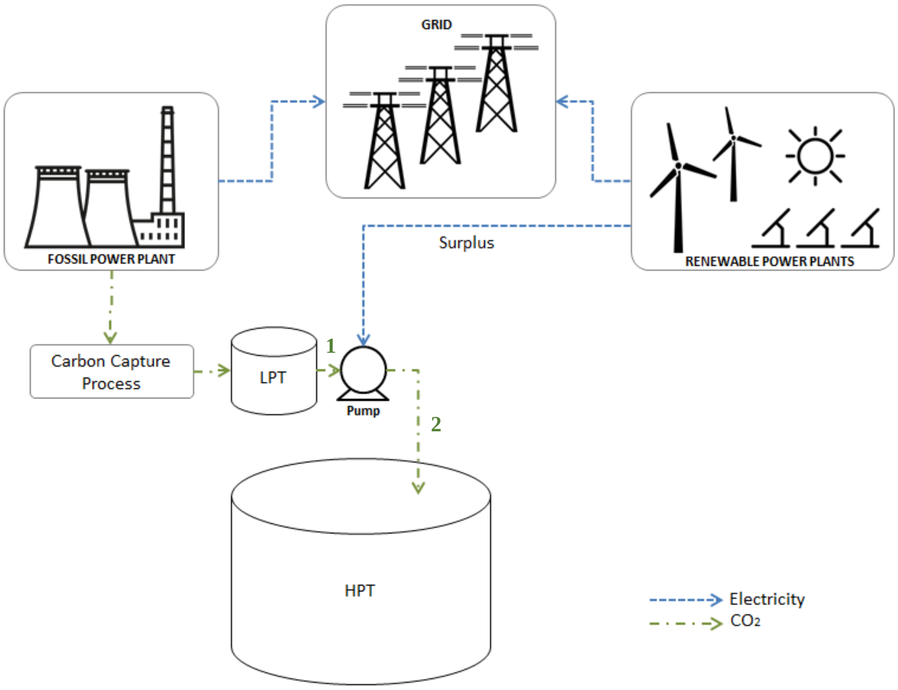

Figure 1. The CCS-ES during charging phase

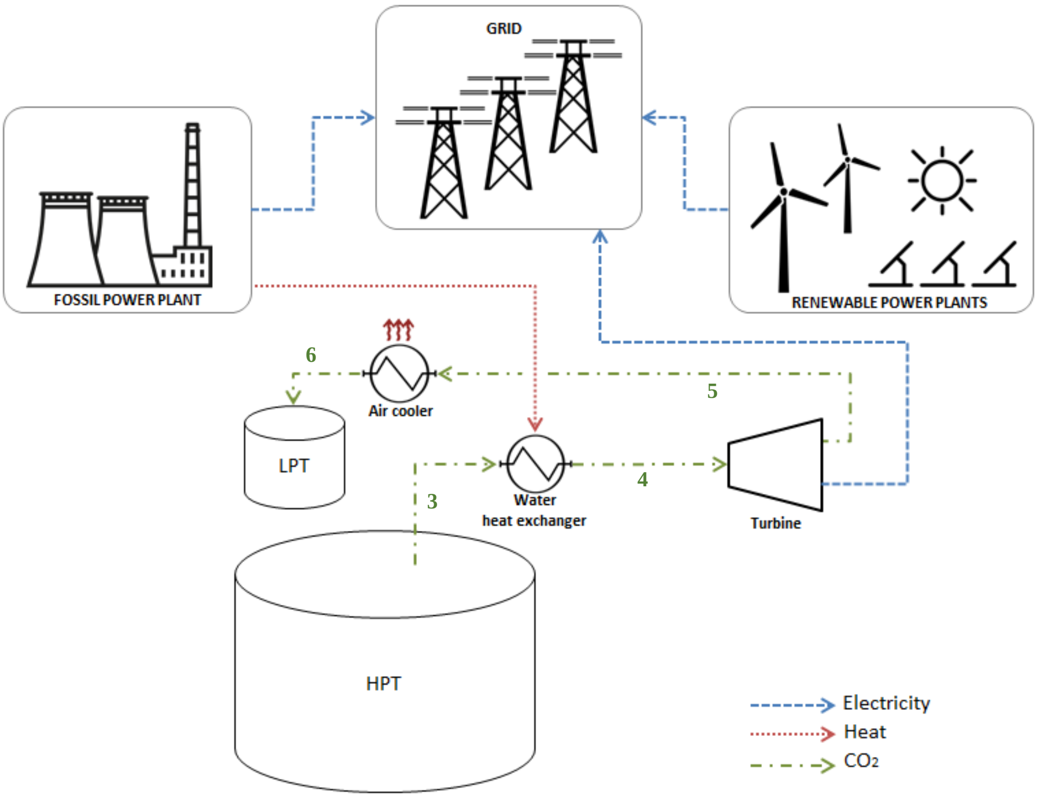

Figure 2. The CCS-ES during discharging phase

It is possible to realize that, after a complete cycle of charging and discharging, the net mass of CO_2 that remains stored in the HPT is a function both of how much energy we want to release to the grid and of how much heat we have provided to the CO_2 in the discharging. The greater the amount of heat received and its temperature, the greater the CO_2 enthalpy to pass through the turbine, so the less CO_2 mass flow rate will be needed to generate the same amount of power. This mass of CO_2 that remains stored in the HPT after a complete cycle we call net mass of CO_2 stored, M_{net}.

The net mass of CO_2 stored is the difference between the stored mass during the charging phase and the released mass that comes back to the LPT during the discharging phase.

A number irreversibilities occurs during the complete cycle and we may not expect that 100% of the provided electrical power in the charging phase will be recovered during discharging phase. On the other hand, when the heat waste is added to the process, it is possible to generate, during discharging phase, the same amount of electrical power provided during charging. Of course, this happens at the cost of using thermal energy. But then it seems reasonable to introduce another paramater to analyse our results: The recovered electrical energy ratio (r_{rec}), shown in Eq.(1).

$$r_{rec}=\frac{W_{recov}}{W_{Grid}} \quad (1)$$

The η_{rec} is the ratio between the amount of energy recovered during the discharging process and the amount of surplus electrical energy received from the grid during the charging process. It may not be confused with a measurement of efficiency, because it does not include other entries of energy, such as heat. This parameter, however, is useful to analyse how much electrical power could be generated in the discharging phase depending on the amount and temperature of heat provided and the amount of CO_2 released in the discharging phase. Or, from another point of view, the (r_{rec}) could be a parameter to measure how much net mass of CO_2 could be stored in a complete cycle depending on the amount and temperature of the heat provided. Nevertheless, the applied methodology and results will be discussed ahead.

It is important to remind that the aim of this paper is to present the concept of the novel CCS-ES system. Therefore, it comprises neither a full exergetic analysis nor a financial feasibility analysis. Actually, this paper discusses the potential that such a system has to store energy and CO_2 and the influence of the heat-waste temperature in this potential. Despite the simplicity of this first analysis, this study opens new opportunities to investigate this novel system. Further studies, including LCOE analysis, detailed simulation including models for the geological wells and a CAPEX/OPEX analysis, will then bring more depth and matutity to the matter.

For this system, it is important that it stays near the fossil fueled power plant for basically 2 reasons: The costs of transporting the CO_2 for other localities and the use of the heat waste from the power plant.

2. METHODOLOGY

For this study, we limited our analysis to the power generation data in Brazil. Nevertheless, the same analysis and methodology could be used to study the potential in other localities. We considered avarage values for the amount of CO_2 and heat waste generated in a single power plant. In Brazil, the Complexo Parnaíba - a natural gas power plant- generates alone 1.4GW, which is about 10% of the total power generated from natural gas in the country. According to EIA (2020), the electrical power generation from natural gas emits about 0.41 kg CO_2/kWh. In this case, the CO_2 emissions in Parnaíba is about 574 tons CO_2/h. In a carbon capture process, usually about 90% of the CO_2 in the flue gas is captured, totaling around 516tons CO_2/h, or 12.4E+6 kg/day. Besides that, a natural gas power plant (NGPP) that uses combined cycle (Brayton plus Rankine cycle), as it is usual, presents a global efficiency of about 60% and generates heat waste at maximum 200^{o}C.

Also, for the surplus energy available, we considered from renewables only the wind and solar power, once hydropower usually has its own energy storage system, by pumping the water back to up. According to ABEEólica(2020) the wind power generation in Brazil is currently 18GW and the solar power is 3.3GW, totaling 21.3GW. It is reasonable to consider a surplus generation of 4h/day, totaling 85.2GWh/day of surplus electrical power coming from the renewables. We also considered that the amount of surplus energy will be shared with different energy storage systems, an that only 20% of this amount was available for our CCS-ES system, which is 17 GWh/day.

Once we decided to measure the surplus energy from renewables in a day period, the other parameters from the fossil power plant will also be used in units of energy/day basis. Table 1 shows the parameters used, according to the information above.

Table 1 – Parameters related to the supply of energy in the system

Parameter		Unit	Value
Surplus Energy from renewables	W_{Grid}	J/day	6.12E+13
Heat waste Temperature in combined cycle	$T_{HW,máx}$	K (^{o}C)	473 (200)
Global efficiency for the NGPP	η_{NGPP}	-	0.6
Electrical energy generated in NGPP	W_{NGPP}	J/day	1.20E+14
Heat waste generated in NGPP	Q_{NGPP}	J/day	4.80E+13
Amount of CO2 daily emitted	$M_{CO2,emit}$	kg/day	1.24E+07

With this study we wanted to answer three basic questions, namely:

(1) How much CO_2 this amount of surplus energy from renewables can daily compress to the HPT?
(2) How much stored energy can be recovered to the grid if we want to keep the power plant carbon neutral (which means that $M_{net}=M_{CO2,emit}$)?
(3) What is the roundtrip efficiency of the energy storage system?

Next we detail the methodology used to answer these questions.

At the charging phase, we applied the 1LTD to the compressor to simulate the mass of CO_2 that could be stored in the high pressure tank (HPT) using the amount of energy received from the grid (W_{Grid}) . We considered that the mechanical and isentropic efficiencies of the compressor were 0.99 and 0.85 respectively. The pressure and temperature of the low pressure tank (LPT) were estimated according to the conditions that the CO_2 comes from the CCS process, which are 5bar and 32°C. We also considered a pressure loss of 5% during the injection in the HPT. The time of charging is 4hours, according to the surplus time duration of the renewables.

At the discharging phase, we applied the 1LTD to the heat exchanger and to the turbine to simulate the mass of CO_2 that would be used in the cycle to generate a certain amount of electrical energy in the turbine. This amount of energy was given by specifying the recovered electrical energy ratio, given by Eq.(1) above, which varied from 0.1 to 1.

The net mass of CO_2 that can be stored after the charging-discharging complete process is then calculated as the difference between the stored mass during the charging and the used mass during discharging. It depends both on the amount of recovered electrical energy in the turbine, given in this case by (r_{rec}), and on the temperature at which the fluid enters the turbine. Put in other words, the greater the amount of energy we want to deliver back to the grid, the less CO_2 remais in the final storage (HPT) for the same amount of heat added to the cycle. And the greater the amount and temperature of the heat added to the cycle during the discharging, the less mass of CO_2 must be released to the turbine. Because of the interdependence of these factors, we chose to generate a graph that shows the amount of CO_2 that remains stored as a function of the amount of energy recovered to the grid, which is here given by the (r_{rec}). In order to understand the influence of the heat-waste temperature, we simulated the discharging phase with different inlet-temperatures for the turbine, varying from 50 to 200°C. We considered that the mechanical and isentropic efficiencies of the turbine were 0.99 and 0.85 respectively. Figure 3 shows the scheme of the methodology used to produce the results. The numbers (1-3) in the OUTPUT stage corresponds to the answers to the three questions we presented above.

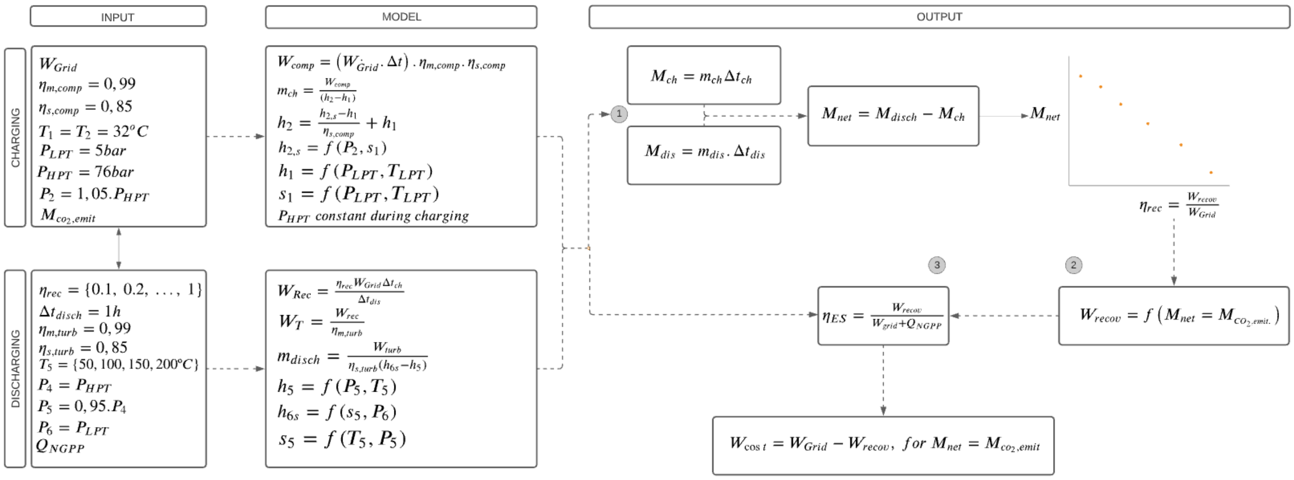

Figure 3. Schematic diagram of the methodology

The expected results show the relationship between the CO_2 net mass stored and the recovered electrical energy ratio for different temperatures. With this result, we are able to see the conditions of heat (temperature) that can be used to achieve the expected benefits of this proposed system and discuss its feasibility. The simulations were made with Python.

3. RESULTS AND DISCUSSION

Figure 4 shows the relation of the net mass of CO_2 stored (M_{net}) and the recovered electrical energy ratio (η_{rec}) for different temperatures, as obtained from the simulation in python. Answering the first of three questions made above, we can see that about $2.5x10^8$kg/day of CO_2 can be compressed to its final storage, with the amount of surplus energy daily available for this system. This amount corresponds to more than 20 times the amount of CO_2 daily produced in this power plant. See the point 'A' in the graph, that corresponds to r_{rec}=0, when the discharging phase has not occurred yet.

During the discharging, as we expected, the higher the heat waste temperature, the less mass of CO_2 needs to be released to the turbine to generate the same amount of energy. The black dashed line shows the amount of CO_2 daily emitted in this natural gas power plant (around $1.24x10^7$kg/day).

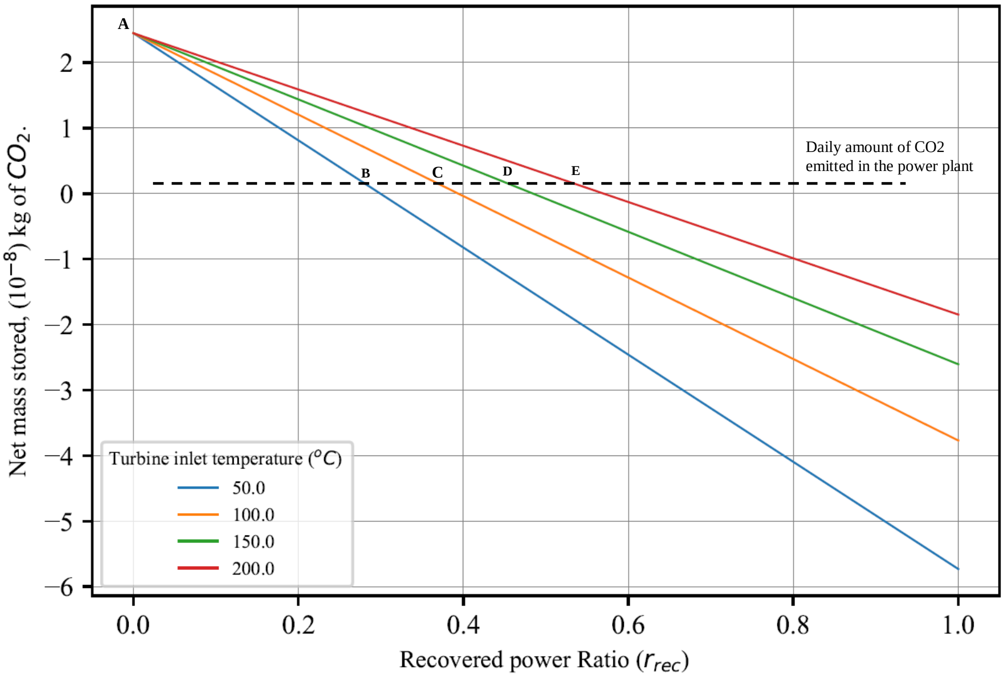

Figure 4. Relation between the net mass of CO_2 stored after discharging and recovered electrical power ratio for different turbine inlet temperatures. Temperatures in ^oC.

The dashed line in Figure 4 helps us to see under which conditions the system must operate for the natural gas power plant to be carbon neutral and what is the influence of this in the recovery of the stored energy. This analysis leads to answer the questions (2) and (3). Table 2 shows the amount of energy that can be recovered to the grid if we want to keep the power plant carbon neutral and also shows the energy storage roundtrip efficiency for different turbine inlet temperatures. It also shows the corresponding recovered power ratio (r_{rec}). The amount of energy was given in units of Joules/day and GW. For this last, we considered 4 hours/day of discharging, corresponding to the peak-time hours in a day. These data are related to the points B, C, D and E in the Figure 4.

Table 2 – Amount of recovered energy (W_{rec}) and roundtrip efficiency (η_{ES}) for the system when the M_{net} (net mass of CO_2 stored) equals to the $M_{CO2,emit}$ (mass of CO_2 emitted in the power plant)

Turbine Inlet Temperature (ºC)	**r_{rec}**	**W_{recov} (J/day)**	**W_{recov} [GW][*]**	**η_{ES}**
50	0.286	1.70E+13	1.21	0.188
100	0.377	2.29E+13	1.59	0.207
150	0.464	2.81E+13	1.95	0.227
200	0.546	3.30E+13	2.29	0.241

[*] Considering 4hours/day of discharging

As expected, the higher the turbine inlet temperature, the higher the amount of energy that can be recovered to the grid using the same amount of CO_2 from the HPT.

One may argue that the system isn't a good energy storage system, given the presented roundtrip efficiencies. It is good to remind, though, that this systems does not have only the purpose of being an energy storage system, but also to respond to the big world problem of reducing CO_2 emissions. The system promises to give the fossil power plant the carbon neutrality and yet work as an energy storage system for peak-time hours. It is also interesting to observe that this system, given the dimensions of CO_2 storage such as a geological well, can store an enormous amount of energy in the form of compressed fluid. Such a system could then be very useful during interseasonal energy demands. Morever, when the well be finally full, the system could still keep operating as an energy storage system alone.

In addition to what has been discussed so far, some observations may be useful. First, the amount of CO_2 that can be compressed during charging phase using the daily available surplus energy from renewables is higher (about 20 times) than that emitted by the fossil power plant . To keep the amount of energy recovered to the grid, this extra mass of CO_2 must be always available to the system. Then, an extra low pressure tank (LPT) should be added to the process to keep this feasible. Moreover, to fully understand the potential of this system, a Capex/Opex analysis might be further conducted.

4. CONCLUSIONS

Such a system, under the condition considered in methodology, has the potential of working both as energy and CO_2 storage system. Although it may not be seen as the most efficient energy storage system alone, this system was thought to work on both fronts: storing carbon and making renewable sources of energy more dispatchable with energy storage. By using low- to medium-temperature heat waste from the fossil power plant, the system could promote carbon neutrality to the fossil power plant while storing energy with a roundtrip efficiency that varies from 18.8% (with heat waste at 50 ^oC) to 24% (with heat waste at 200 ^oC).

Financial and technical limitations must be investigated in order to obtain a deeper view of the impact of this proposed system and its real feasability. For now, we suggest that this system has technical potential to be explored, specially if using the medium-temperature heat waste from the power plant.

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