ABSOLUTE LIFE CYCLE OPTIMIZATION OF THE CDR-POWER NEXUS

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Abstract

Carbon dioxide removal is deemed necessary to limit the temperature rise well below 2 °C in addition to emissions reduction efforts. The broad portfolio of technologies that can deliver negative emissions calls for integrated analyses to explore the synergies among the available options and the power sector. These analyses should be carried out on a regional level to understand the potential local benefits and implications of carbon removal. In this work, we perform a life cycle optimization of the European Union energy system where bioenergy and direct air CO_2 capture with storage (BECCS and DACCS, respectively) are deployed to provide negative emissions. We analyze three scenarios within the planetary boundaries framework and explore how the portfolio of negative emissions and the power mix change. We find that BECCS can be deployed on a larger scale to maximize the removal or to minimize costs, although it impacts particulate matter significantly. A larger share of removal from DACCS is found in the minimum impact scenario. Additionally, a shift from nuclear power to wind or solar reduces the pressure on the resource use category.

Keywords

Carbon dioxide removal, EU power mix planning, Planetary boundaries.

Introduction

Climate policies aiming at meeting the 2 °C target require the deployment of carbon dioxide removal (CDR) options to compensate for historical emissions and future ones from hard-to-decarbonize sectors, together with emissions reduction efforts (IPCC, 2022). CDR involves the sequestration of CO_2 from the atmosphere and its long-term storage using negative emissions technologies and practices (NETPs) (Jeswani et al., 2022). NETPs range from natural solutions to more engineered ones, such as bioenergy and direct air CO_2 capture with storage (BECCS and DACCS, respectively), among many others (Morrow et al., 2020). By deploying BECCS, the CO_2 is captured during the plant's growth phase, and the biomass, which acts as a natural sink, is then converted into valuable products such as electricity and heat. In contrast, DACCS employs solid sorbents or aqueous solvents as capture agents (Keith et al., 2018). The process of obtaining a clean and reliable energy source from BECCS is well understood; nonetheless, significant impacts arise in ecosystems and biodiversity. These effects could be mitigated by deploying DACCS, which, in turn, requires a large amount of heat and power. Thus, it becomes evident that synergies between these NETPs should be exploited to achieve the CDR required to meet the Agreement's target with little collateral damage.

Until very recently, the study and advancement of BECCS and DACCS as solutions to climate change were carried out independently and mainly from a techno-economical perspective, neglecting the benefits of their

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coupling and integration in energy systems to enable a removal at the gigatonne scale. In the last years, regionalized models have assessed the potential of hybrid BECCS-DACCS power systems; for example, we highlight the work by Daggash et al. (2019) for the United Kingdom or Sagues et al. (2019) for the United States.

However, the deployment of CDR options still faces major concerns regarding their environmental and social implications (Lenzi et al., 2018). Thus, their potential should be evaluated from an environmental perspective considering regionalized settings whenever data is available. Additionally, given that these options are assessed within long-term planning energy systems models, the results are affected by a considerable degree of uncertainty (Fajardy et al., 2019). Along these lines, Grant and co-authors (2021) carried out a pioneering work evaluating CDR uncertainty at a global scale using the TIAM-Grantham model in stochastic scenarios.

Here we build on previous work focusing on the co-benefits of deploying BECCS and DACCS. In a recent publication, Cobo and co-workers (2022) assessed the long-term benefits of these two technologies on the global human and planetary health, while Galán-Martín et al. (2021) evaluated the implications of delaying BECCS and DACCS CDR in the European Union (EU) energy system. Despite these contributions, a detailed regionalized life cycle optimization analysis of the two NETPs considering the nexus with the power mix is still missing. Moreover, previous environmental studies of NETPs often rely on standard LCA metrics lacking absolute thresholds, which provide limited insights into the global implications of deploying them at scale. Hence, following the recommendations in Weidner et al. (2022), here we integrate the planetary boundaries (PBs) framework into a model of the CDR-power nexus to optimize the absolute environmental sustainability level of the system, previously performed for a BECCS supply chain alone (Negri et al., 2022). Our results shed light on critical trade-offs between environmental categories when deploying CDR at scale that should be considered in policy-making. Lastly, we carry out a sensitivity analysis to provide confidence intervals of the system's net total emissions and cost in 2100 considering uncertainty in the energy demand.

Methodology

We adapt the multi-period (2020 – 2100) RAPID model by Galán-Martín et al. to carry out a life cycle analysis (LCA) of the EU energy system coupled with CDR using absolute sustainability metrics. Specifically, we analyze the impact on the PBs of meeting the energy demand in the EU at each period in the given time horizon by combining optimization and scenario analysis. Due to space limitations, we refer to the publication of Galán-Martín et al. for the full data, model description and assumptions.

We run the problem in the General Algebraic Modelling System software (GAMS, Brooke et al., 1992) version 35.2.0 coupled with CPLEX on an Intel i9-9900 CPU, 3.10 GHz computer with 32 GB RAM.

Planetary Boundaries Framework

Absolute environmental sustainability assessments are based on the Earth's carrying capacity; well-defined limits that identify the safe operating space (SOS) have been determined for each PB category. Transgressing the SOS implies that an unstable status of the Planet might be triggered where humanity cannot develop and prosper. The link between the LCA framework and the PBs is made possible by the characterization factors (CFs) that convert the life cycle inventory (LCI) into impacts. Here, we assess the system's environmental performance using 16 indicators of the Environmental Footprint (EF) method and the SOS limits reported by Sala et al. (2020). The life cycle inventory is implemented in SimaPro v. 9.1.0.8 using Ecoinvent v3.5 to retrieve the foreground and background data. The functional unit of this study is to meet the EU energy demand and the analysis presented is cradle-to-gate.

We are interested in analyzing the impacts from a regional perspective. Therefore, we calculate the share of the SOS assigned to the EU based on an egalitarian principle (PB^{EU}). For convenience, the population is updated according to a linear increase over the time horizon. We use demographic projections for 2100 given by the United Nations, which include uncertainties (United Nations, 2019).

We consider three scenarios that are optimized independently: maximum carbon dioxide removal, minimum impact and minimum cost. Firstly, we want to assess the impacts on the Earth's systems for the solution given by Galán-Martín et al. Then, taking the previous solution as a starting point, we minimize the global impact and analyze how the energy mix and the CDR options change. Lastly, we provide a comparison with the minimum cost scenario where the CDR target must be constrained to a minimum value to force the deployment of BECCS and DACCS. In this case, we fix the CDR to an arbitrary value of 50.00 Gt CO_2 in 2100, among those explored by Galán-Martín and co-authors.

We use an aggregated metric to consider the global transgression (tl), which includes all the categories with equal relevance.

Firstly, the total impact (imp_{tk}) is determined from the LCI using the CFs for each unit of flow i of the system as in Eq. (1). The set k refers to the 16 PBs metrics, while E_{ti} is the elementary flow i at each time period t. In our study, we consider regionalized input data for each activity.

$$\mathrm{imp_{tk}} = \sum_i \mathrm{CF_{ik}}\,\mathrm{E_{ti}} \;\; \forall \;\; t, k \tag{1}$$

Then, we sum up the relative contributions of all the k categories to calculate tl at the end of the time horizon as reported in Eq. (2).

The new variable obtained is incorporated into the model and minimized as the objective function in the second scenario.

$$\text{tl} = \sum_t \sum_k \frac{\text{imp}_{\text{tk}}}{\text{PB}_{\text{tk}}^{\text{EU}}} \tag{2}$$

The rationale for aggregating all the categories into tl is that a single score metric defining the overall transgression level is more convenient for communicating with stakeholders and policymakers. We refer to the recent review by Weidner and co-authors for a more exhaustive overview of techniques to integrate absolute environmental metrics into optimization.

Sensitivity Analysis

The length of the time horizon explored and the amount of data to input into the model might raise concerns about the robustness of the results. Indeed, fully deterministic models could lead to spurious conclusions if a parameter deviates substantially from the nominal value.

Here, we carry out a scenario analysis to evaluate the effect of uncertainty considering exogenous parameters, *i.e.*, decision-independent (Apap and Grossmann, 2017), on the CDR and the total cost.

We are aware that by considering a distribution of values of the energy demand, the functional unit of our study changes. Consequently, a comparative analysis of the different systems would not be in accordance with the ISO standards for LCA. Therefore, we explore two scenarios, maximum removal and minimum cost subject to a net 50.00 Gt CO_2 removal in 2100. The results obtained are meant to quantify the difference in the CDR and cost from the nominal value for different energy requirements, and they are not meant to be for comparative purposes among the scenarios themselves.

We define 500 scenarios to obtain a representative data distribution and we consider that the energy demand of each country in the EU at each time period can vary within $\pm 20\%$ with respect to the nominal value following a normal distribution.

Results and Discussion

Planetary Boundaries Analysis

RAPID identifies the optimal portfolio of technologies to meet the energy demand of the EU system in each time period until 2100, including BECCS and DACCS as NETPs to reach the given carbon target. In this analysis, we are interested in how the energy mix and the share of CDR options change within each scenario. We identify the implications that the selected CDR technologies have on the PBs categories to provide valuable insights that will facilitate an informed deployment of these technologies.

A comparison of the net CDR in 2100 and the cumulative transgression level at the end of the time horizon in each scenario are reported in Table 1.

Notably, as expected, the highest CDR is attained in the maximum CDR scenario, in which only CO_2 emissions are considered in the environmental objective. In this solution, PBs categories such as particulate matter and resource use, energy carriers transgress their SOS by almost 40% and 60%, respectively. It is clear that despite the system's potential to mitigate climate change, burden-shifting occurs in other categories, which are equally relevant. Therefore, maximizing carbon dioxide removal might not be the most favorable approach from an environmental standpoint. In contrast, when the total transgression is minimized, a lower net CDR is obtained, accounting for contributions other than CO_2 emissions. As a consequence, by minimizing tl, a reduction of 22% and 44% in particulate matter and resource use, energy carriers, respectively, occurs. Lastly, for a net 50.00 Gt CO_2 removal in 2100, the PBs total transgression metric worsens substantially because climate change declines sharply.

Table 1. Scenarios results: net CDR and impact metric. The CDR (*) of the minimum cost scenarios is an active constraint. The removal is reported as negative emissions in 2100.

Scenario	Net CDR [Gt CO_2]	Impact tl
Maximum CDR	−73.41	22.78
Minimum impact	−67.26	3.52
Minimum cost	−50.00*	63.64

We report in Figure 1 the performance of the three scenarios on the most relevant PBs categories. It is evident that the maximum removal scenario performs best in climate change while showing the highest impacts in the other categories, comparable to the minimum cost scenario.

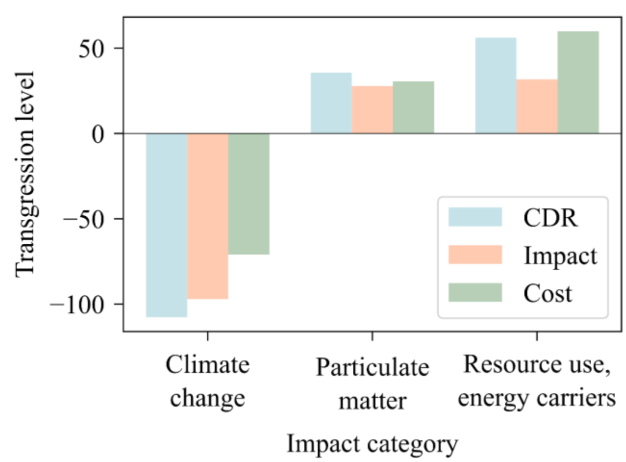

Figure 1. Cumulative transgression level of the categories contributing more significantly to the global impact in 2100. The three scenarios are identified as 'CDR', 'Impact', 'Cost'.

Next, we analyze the role that the two NETPs included in the EU energy system play in the gross removal. We report in Table 2 the share of gross CO_2 removal from BECCS and DACCS in the three scenarios. Given its higher TRL and larger capacity in the geographical region considered, BECCS is responsible for most of the removal in all the scenarios. At the same time, it also contributes to providing a clean energy source. Hence, its benefit is twofold, and its deployment is encouraged. However, when looking more closely at the effects of the CDR options on the particulate matter category, we find that the impact on this category is proportional to the BECCS removal at each time period. This correlation is also evident by comparing the trend shown in Figure 1 to the gross removal reported in Table 2. Therefore, given that the particulate matter category is one of the major positive contributions to the global transgression level, in the second scenario explored, the capacity of BECCS is reduced and DACCS capacity increases to compensate for the removal while the global impact is minimized. In contrast, DACCS is more expensive per Gt CO_2 removed; therefore, when the minimization of the system's total cost is sought, its contribution to the overall CDR is reduced, being the lowest among all the scenarios.

These results should also be analyzed in light of the initial capacity installed and capacity expansion factor, which are based on current data and scale ambitions in our model, for which BECCS has a clear advantage over DACCS.

Table 2. Scenarios results: gross removal from BECCS and DACCS in 2100.

Scenario	Removal BECCS [Gt CO_2]	Removal DACCS [Gt CO_2]
Maximum CDR	64.03	21.45
Minimum impact	51.30	31.76
Minimum cost	53.55	20.88

We also note that other categories, such as land use and freshwater use, are affected by the deployment of BECCS because of the resources employed for energy crop cultivation. In Figure 2, we show the correlation between the BECCS removal potential and the land availability in the regions of the EU, according to the input data reported by Galán-Martín et al. Eight countries, among which Spain, Italy, France, Germany and the United Kingdom, contribute to 81% of the total removal in the minimum impact scenario given their higher land availability for the cultivation of the biomass feedstock considered.

We further analyze the solutions obtained in each scenario regarding the overall electricity generation. The power mix for the different scenarios is provided in Figure 3. The outer ring of the figure shows the results of the minimum cost scenario, while the inner one of the maximum removal. The ring in the middle represents the mix corresponding to the minimum impact.

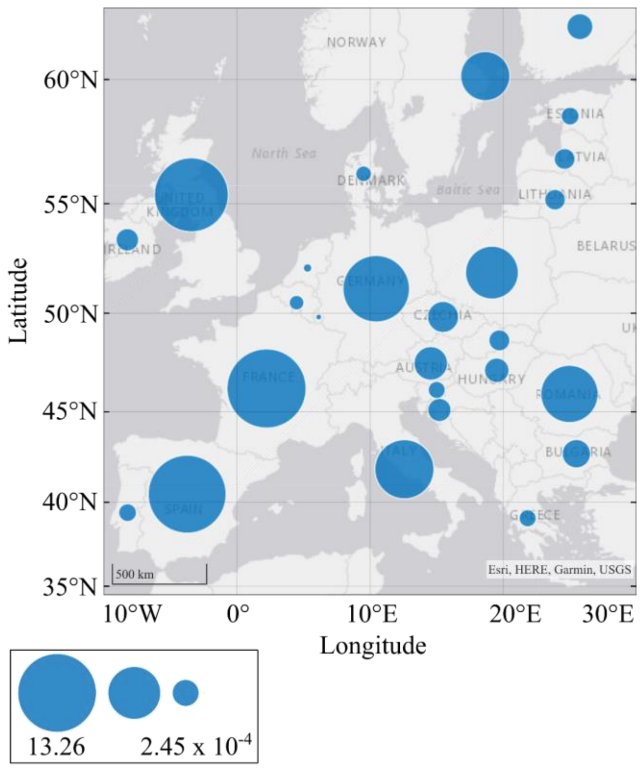

Figure 2. Carbon dioxide removal in the EU in the minimum impact scenario. The removal is proportional to the land availability of the countries.

As mentioned above, the two PBs categories impacted the most are particulate matter and resource use, energy carriers. On the one hand, the reduction of impacts on particulate matter is achieved by shifting the CDR from BECCS to DACCS. On the other hand, the impact on resource use, energy carriers can be reduced by substituting nuclear power with a higher share of electricity from alternative sources, such as wind or solar. As shown in Figure 3, compared to the maximum CDR case, the minimum impact scenario has an increased capacity in solar and less nuclear power, whereas the other technologies remain almost constant. The power mix of the minimum cost scenario is the most heterogeneous, including 11 electricity technologies. However, solar and wind installed capacity is lower than in the previous cases.

The highest share of electricity production in the whole EU system is provided by the same countries that are also responsible for 81% of the total removal, mentioned previously, as bioenergy contributes to the overall EU mix. In all the scenarios, France, Spain and Germany contribute to the majority of power generation, although the energy mixes differ depending on the objective function. To clarify how the shift in the power mix takes place, we take France as an example, which is the first electricity producer in terms of TWh. In the maximum removal scenario, the French mix is almost entirely characterized by nuclear and wind power. Oppositely, when the global impact is minimized, nuclear capacity is greatly reduced and substituted by solar. Lastly, in the minimum cost, nuclear power is reintroduced into the mix, but a combination of other technologies is also deployed.

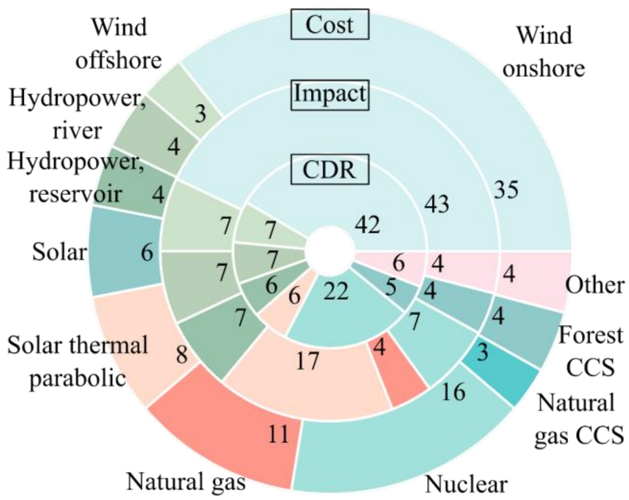

Figure 3. Scenarios results: energy mix. The outer ring corresponds to the minimum cost scenario, while the inner one to the maximum CDR. In the middle, the minimum impact is represented. The percentage of electricity generated by each technology is reported on top of the corresponding arc (±0.5%).

Notably, negative emissions technologies require substantial capital investment and are not yet implemented at an economically appealing scale. One option, still not widely and uniformly adopted in the EU, is to enforce carbon prices on direct emissions, which could make CDR options more appealing. Pietzcker et al. (2021) demonstrated that a carbon price of 129 Eur/tCO_2 is needed in an ambitious scenario of 54% emissions reduction in 2030 compared to 1990. Additionally, as the carbon price reaches 100 Eur/tCO_2, the model starts investing in BECCS deployment.

Sensitivity Analysis

We run RAPID for different electricity demand scenarios to understand the implications of the uncertainty in the input parameter on the net CDR and total cost. The results reported in this section represent different system configurations and are to be interpreted with respect to the nominal solution reported in Table 1. Figures 4 and 5 report the data kernel distribution, in addition to the median as a white dot and the interquartile range, leaving out the points that are considered outliers. The nominal value, *i.e.*, the solution of the deterministic model reported in Table 1, is also shown as a yellow dot in the boxplot.

The uncertainty in the maximum carbon dioxide removal is represented in Figure 4. Notably, the distribution of the data is not symmetric around the mean −71.52 Gt CO_2, with a standard deviation of 4.99 Gt CO_2. The highest density of the data is shown close to the minimum, approximately −80.00 Gt CO_2, while the probability density is lower at −50.00 Gt CO_2. The coefficient of variation of the dataset is −6.98.

We note that the maximum CDR that could be achieved is limited by the technology deployment rate and, most importantly, the CO_2 storage availability. These parameters are extremely critical especially when the deployment of NETPs is delayed, *i.e.*, we do not act now.

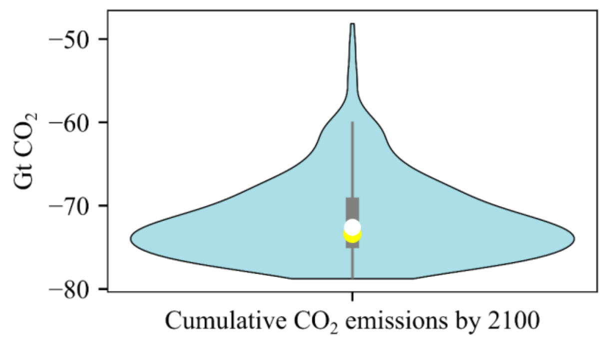

Figure 4. Maximum removal obtained considering uncertainty in the electricity demand in 2100. The yellow dot represents the solution to the deterministic model.

The distribution of the total cost for a net removal of 50.00 Gt CO_2 in 2100 is reported in Figure 5. The cost distribution is approximately uniform and has a mean value of 30.75 trillion $Euro_{2015}$ with a standard deviation of 5.96 trillion $Euro_{2015}$. Compared to the results of the maximum CDR scenario, a coefficient of variation of 19.37 is attained, meaning that the variability of the results is higher.

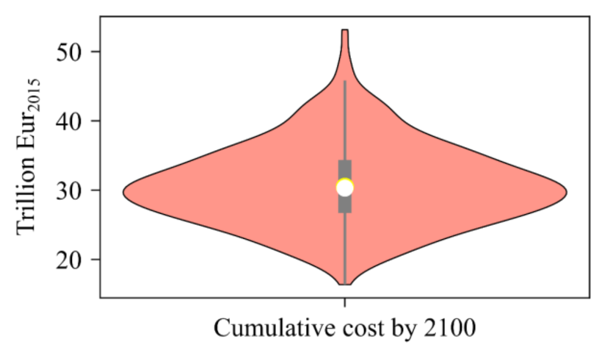

Figure 5. Minimum cost subject to 50.00 Gt CO_2 net removal in 2100 considering uncertainty in the electricity demand. The yellow dot represents the solution to the deterministic model.

Compared to the analysis in Galán-Martín et al., the uncertainty in the energy demand leads to higher variability in the cost than by considering the uncertainty in the biomass availability or in the CAPEX parameter. Indeed, the electricity demand strongly affects the planning of the energy system, including technologies capacities, operating expenses and the CDR options installation.

Conclusions

We carried out a life cycle optimization of the European Union power mix where BECCS and DACCS can be deployed over the time horizon 2020 – 2100. We used the planetary boundaries framework to assess the absolute environmental sustainability of the CDR-power nexus. The functional unit is the energy demand at each time period in a cradle-to-gate analysis. We interpret the solutions of three scenarios, namely maximum removal, minimum impact and minimum cost subject to 50.00 Gt of net removal focusing on the resulting carbon dioxide removal by BECCS and DACCS and the energy mix.

In all the scenarios, BECCS provides the highest share of carbon removal. However, it is also responsible for one of the most relevant impacts in the global transgression level metric, *i.e.*, on particulate matter. We identify a positive correlation between the impact on particulate matter and the BECCS removal. Consequently, a larger share of DACCS is present when the impact metric is minimized. On the other hand, when the minimum cost solution is sought, DACCS capacity is again greatly reduced, given its high removal cost.

The second most critical contributor to the global transgression level is resource use, energy carriers, mainly linked to the power technologies. In particular, nuclear power exacerbates this indicator. When looking at the power mix, we conclude that the solutions to the maximum removal and minimum impact scenario are rather similar. However, when the global impacts are minimized, nuclear power installed capacity decreases and is substituted with solar. Lastly, the minimum cost scenario is characterized by the most heterogeneous mix.

We also find that a set of countries in the European Union, including Spain, France and Germany, is responsible for the most significant share of removal and electricity production at the same time.

Lastly, we carry out a simple scenario-based uncertainty analysis, finding that the net carbon dioxide removal ranges between −80.00 and −50.00 Gt CO_2 in 2100, mainly limited by the CO_2 geological storage capacity. On the other hand, the distribution of the total cost shows a more uniform distribution of the data in the range 15.00 – 55.00 trillion Eur_{2015}. By introducing uncertainty in the energy demand, higher variability in the total cost is obtained rather than in the removal potential.

Our study demonstrates that there are clear benefits in analyzing the nexus carbon removal-power mix. The use of regionalized data is also paramount to understanding the local implications of negative emissions on power generation and other regional parameters, such as land use.

Further analyses should include a more thorough assessment of the uncertainty to ensure that the solution provided is sound over the long time horizon.

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