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COMMENTARY

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Key Points:

- As part of a highly renewable power system, Direct Air Capture (DAC) has substantial carbon dioxide removal potential
- DAC can complement volatile renewable power generation by providing flexibility
- Assessments of cobenefits of different technologies for negative emission, flexibility provision, and sector coupling are needed

Supporting Information:

- Supporting Information S1

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Negative Emission Potential of Direct Air Capture Powered by Renewable Excess Electricity in Europe

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Abstract The mitigation of climate change requires fast reductions in greenhouse gas emissions and calls for fundamental transitions of energy systems. In most places, the increased exploitation of variable renewable sources (wind and solar) forms the backbone of these transitions. To remain consistent with the Paris Agreement temperature goals, negative emission technologies will likely be needed to achieve net zero emissions in the second half of the century. In integrated assessment models, negative emissions are typically realized through land-based approaches. However, due to their coarse temporal and spatial resolution, such models might underestimate the potential of decentrally deployable and flexible technologies such as Direct Air Capture (DAC). Based on validated high-resolution power generation time series, we show that DAC can extract CO_2 from the atmosphere and facilitate the integration of variable renewables at the same time. It is a promising flexibility provider as it can be ramped within minutes. Our results show that negative emissions of up to 500 Mt CO_2/year in Europe may be achievable by using renewable excess energy only. Electricity systems with high shares of volatile renewables will induce excess generation events during which electricity is cheap thereby lowering the operational costs of DAC. If investment costs can be sufficiently reduced, this may render very energy intensive but highly flexible technologies such as DAC viable.

Plain Language Summary There is a finite amount of greenhouse gases that humankind can emit into the atmosphere before the 1.5 and 2 °C climate targets are exceeded. This calls for emission reductions in all sectors of human activity, in particular in the energy sector. In many countries, energy transitions have already led to the expansion of variable renewable energy technologies that depend strongly on weather such as wind and solar. In addition to the expansion of renewable energy, scenarios that achieve the 1.5 or 2 °C target require negative carbon emissions later in the century to make up for insufficient emission reductions so far. In this study, we investigate the cobenefits of a negative emission technology called Direct Air Capture (DAC) and a high share of wind and solar energy. The advantage of DAC is that it can in principle be deployed decentrally and it can be switched on and off very quickly. It is thus possible to use DAC to smooth the variability of renewable power generation while achieving negative emissions. Our study focuses on the technical aspects of including DAC in the power system and does not provide a thorough assessment of the economic viability of DAC deployment.

1. Introduction

The achievement of the Paris Agreement climate goals is difficult to impossible without the availability of negative carbon emissions, as the reduction of greenhouse gas emissions to date is insufficient (Schleussner et al., 2016). Halving global CO_2 emissions every decade from 2020 onward as well as upscaling of negative emission technologies is required to reach global net zero CO_2 emissions by midcentury (Rockström et al., 2017). The exact amount of required negative CO_2 emissions depends on a range of scenario assumptions, first and foremost the stringency of near-term emission reductions (van Vuuren et al., 2018). Implementing negative emissions at the scale demanded by energy economic models requires large-scale investments (Fuss et al., 2014). While substantial progress in the deployment of renewable energies has been seen over recent years, progress on negative emission falls behind expectations (Peters et al., 2017).

A multitude of negative emission technologies exists. Minx et al. (2018) provide an overview and distinguish seven different technologies: afforestation and reforestation, soil carbon sequestration, biochar, bioenergy in combination with carbon capture and storage (BECCS), enhanced weathering, ocean fertilization, and Direct Air Capture (DAC). Among them, BECCS features most prominently (Minx et al., 2017). Along with other land-based approaches, it requires substantial amounts of land and water raising sustainability concerns (Smith et al., 2015). The focus on BECCS or afforestation and reforestation in energy economic models may be partly linked to outdated assumptions about the development of renewable energy costs that lead to overly conservative deployment (Creutzig et al., 2017). As recently argued by van Vuuren et al. (2017), an open discussion of negative emission technologies is urgently needed. For completeness, this discussion has to include DAC.

2. DAC May Complement Volatile Renewables

The availability of very cheap renewable energy, including occasional negative prices (Kyritsis et al., 2017), provides an opportunity to implement negative emission technologies that were previously uneconomic. For example, DAC has been assessed to be of limited applicability due to high costs (two-thirds capital and one-third operational) and energy demand at least in the near term (Smith et al., 2015). However, substantial amounts of excess energy are available in highly renewable power systems due to temporal and spatial volatility of these energy sources (e.g., Rodriguez et al., 2014). To ensure system stability and to avoid wasting electricity, flexibility options that harmonize generation and loads are needed (Kondziella & Bruckner, 2016; Schäfer et al., 2018). Various technologies can provide this flexibility (e.g., power-to-gas/heat, dispatchable renewables, and demand-side-management), and all of them will compete in a real-world market situation. Without touching the intricate and uncertain economic comparison between the different flexibility providers, we want to expand this list by DAC that can also provide this system service, as it can be ramped within minutes (Climeworks, 2017). Moreover, it can be deployed in decentral units, which may alleviate transmission grid congestions and corresponding costs (Wohland et al., 2018). DAC could thus in principle be complementary to the fast expansion of renewables.

Here we explore the potential of negative emissions by integrating DAC in a stylized simulation of the European electricity system. We follow an optimistic scenario for European cooperation in assuming that all benefits from interstate balancing are implemented. This scenario provides a lower bound for the usage of DAC because grid limitations increase the amount of excess energy. Based on validated long-term time series for photovoltaics and wind power generation in 28 states (Pfenninger & Staffell, 2016; Staffell & Pfenninger, 2016), we run a simple energy balance model that accounts for storage but neglects other flexibility options (e.g., sector coupling and demand-side management). The storage strategy is based on the filling level and a day-ahead forecast of residual loads (see the supporting information). DAC is assumed to become available at scale and is modeled for different second-order efficiencies as proposed by House et al. (2011). Unless explicitly stated, we conservatively assume that the heat needed for DAC is electricity based. During shortfall in the generation of renewable energy, we assume open-cycle gas power plants will provide backup energy. Although such a stylized experimental design does not allow for robust projections of technology deployment, it yields interesting insights into fundamental cobenefits of DAC and highly renewable systems.

3. System Requirements for Net Negative Emissions

DAC contributes relevant amounts of negative emissions only if at least 80% of the electricity are renewable, independent on the installed DAC capacity (see Figure 1). DAC contributes significantly earlier in smaller power systems but backup emissions are also higher (see Figure S2). This indicates potential for early deployment in conjunction with progressing grid extensions. Current national renewable contributions are still substantially smaller. For example, in 2017 the German power system generated 28% from wind and solar although some of its federal states already exceeded 100%. As expected, large negative emissions require large DAC capacities and renewable penetrations. Net negative emissions at very high penetrations can exceed 500 Mt CO_2 although the viability of such high penetrations is unclear. For a DAC capacity of 300 GW, net emissions roughly become a linear function of the penetration. For comparison, the European net generating capacity was about 1,000 GW in late 2015 (ENTSOE, 2018).

Storage technologies and DAC are not competing but complementary: Increases in storage size allow for reductions of remaining carbon emissions and enable more efficient usage of DAC units. Their codependency

10.1029/2018EF000954

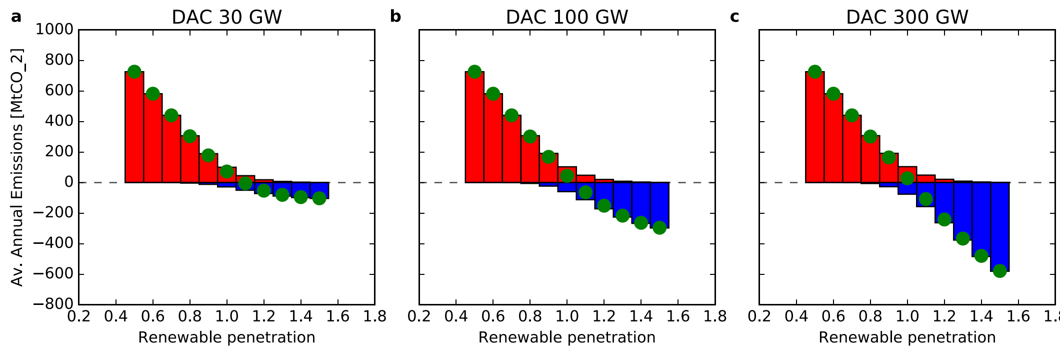

Figure 1. European CO_2 emissions versus renewable penetration for different DAC capacities at a storage size of one average load day. Red bars denote emissions from open-cycle gas turbines that are used for backup. Blue indicates negative emissions from DAC. Green circles denote net emissions. DAC = Direct Air Capture.

in order to reach a hypothetical negative emission target of 500 Mt CO_2 is shown in Figure 2. Below a DAC capacity of roughly 130 GW, the target is infeasible. Above that limit, necessary penetrations generally decrease with increasing DAC capacities and storage sizes.

Our DAC energy estimates are based on the upper bounds provided by a producer named Climeworks (Lozanovski et al., 2014). They are consistent with other reports (Keith et al., 2018; Socolow et al., 2011) and the Climeworks second-order efficiency (5.5%) is slightly lower than in the two other studies (6.3% and 6.9%, respectively). We refer to supporting information Text S1.4 for more details. Since we also assume that heat is entirely generated from electricity, our estimates can be seen as conservative. Energy requirements could be substantially lowered if the technology advances or if the heat partly comes from sources other than electricity. For example, the second-order efficiency would increase from $\eta = 5.5\%$ to $\eta = 9.7\%$, and energy needs drop by more than 40%, if half the heat came from other sources (see Figure S3). Similarly, inclusion of dispatchable renewables such as bioenergy, hydro power and concentrated solar (Pfenninger et al., 2014) would allow parts of the backup to be carbon neutral and thereby facilitating net negative emissions.

4. DAC Merits Thorough Assessments

Our results suggest that DAC has the potential to fully complement highly renewable power systems. This is due to its flexibility and decentrality, which can be advantageous for system integration of high shares of volatile renewables. DAC also requires less land and water resources than BECCS. We thus argue that

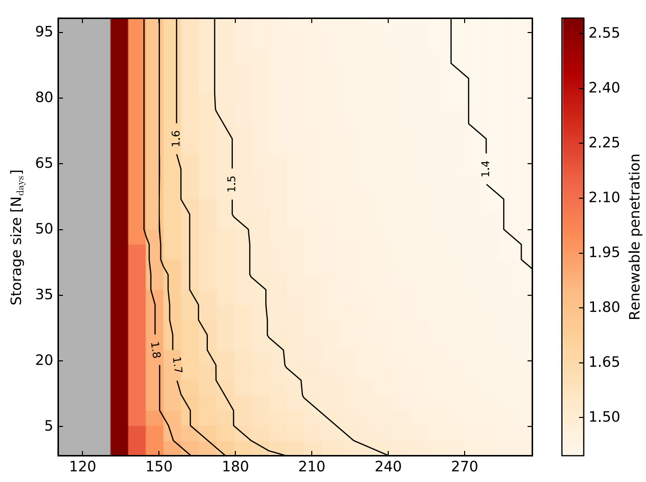

Figure 2. Codependency of storage size, DAC capacity, and renewable penetration to reach a negative emission target of 500 Mt CO_2/year. Colors and contours denote the necessary renewable penetration. Gray denotes infeasibility given the combination of storage size and DAC capacity. The storage size is given in units of the average daily load. DAC = Direct Air Capture.

DAC should be intensively researched. In addition to the technological development of DAC, more realistic energy system simulations that quantify cobenefits and competitions of different technologies are needed. For instance, coupling the heating and transport sector to the electricity system can also provide flexibility (Brown et al., 2018; Connolly et al., 2016) and power to hydrogen may help to decarbonize the industrial sector (Welder et al., 2018). Present-day global energy economic integrated assessment models are not necessarily well suited, because they do not resolve the high-frequency generation dynamics explicitly and hence may underestimate the potential of DAC. Currently high investment costs for DAC are not prohibitive as there will likely be massive potentials for cost reductions as the technology matures and is scaled up (Keith et al., 2018; Lackner et al., 2012). Scenario studies should consider steep learning curves as highlighted by the recent development in the photovoltaics sector (Creutzig et al., 2017). While the investment costs may thus be brought down, potential revenues might increase substantially. For instance, Brown et al. (2018) report CO_2 shadow prices of at least 400 Euro/t_{CO_2} to reach a 95% emission reduction in the electricity, heating, and land-based transport sector. Current prices of EU emission allowances are more than 1 order of magnitude lower.

We have mapped out energy needs and system requirements of a 500 Mt CO_2/year DAC contribution for Europe. If extended globally, DAC could contribute substantially to required end of century negative emissions of 7–22 Gt CO_2/year under Paris Agreement compatible mitigation scenarios (Smith et al., 2015). The system requirements to achieve such rates are very ambitious under our conservative estimates, but substantial potential for increased DAC efficiency exists (see Figure S3). However, discussions of system integration potential of negative emission technologies should not divert attention from the need of very stringent emission reductions in the near term (Schleussner et al., 2016).

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References

Brown, T., Schlachtberger, D., Kies, A., Schramm, S., & Greiner, M. (2018). Synergies of sector coupling and transmission reinforcement in a cost-optimised, highly renewable European energy system. *Energy*, *160*, 720–739. https://doi.org/10.1016/j.energy.2018.06.222

Climeworks (2017). Personal communication with Valentin Gutknecht (Marketing & Communications).

Connolly, D., Lund, H., & Mathiesen, B. (2016). Smart Energy Europe: The technical and economic impact of one potential 100% renewable energy scenario for the European Union. *Renewable and Sustainable Energy Reviews*, *60*, 1634–1653. https://doi.org/10.1016/j.rser.2016.02.025

Creutzig, F., Agoston, P., Goldschmidt, J. C., Luderer, G., Nemet, G., & Pietzcker, R. C. (2017). The underestimated potential of solar energy to mitigate climate change. *Nature Energy*, *2*(9), 17140. https://doi.org/10.1038/nenergy.2017.140

ENTSOE (2018). Net generating capacity on december 31st 2015 (Database: 05.02.2018).

Fuss, S., Canadell, J. G., Peters, G. P., Tavoni, M., Andrew, R. M., Ciais, P., et al. (2014). Betting on negative emissions. *Nature Climate Change*, *4*(10), 850–853.

House, K. Z., Baclig, A. C., Ranjan, M., van Nierop, E. A., Wilcox, J., & Herzog, H. J. (2011). Economic and energetic analysis of capturing CO_2 from ambient air. *Proceedings of the National Academy of Sciences*, *108*(51), 20,428–20,433. https://doi.org/10.1073/pnas.1012253108

Keith, D. W., Holmes, G., Angelo, D. S., & Heidel, K. (2018). A process for capturing CO_2 from the atmosphere. *Joule*, *2*, 1–22. https://doi.org/10.1016/j.joule.2018.05.006

Kondziella, H., & Bruckner, T. (2016). Flexibility requirements of renewable energy based electricity systems – a review of research results and methodologies. *Renewable and Sustainable Energy Reviews*, *53*, 10–22. https://doi.org/10.1016/j.rser.2015.07.199

Kyritsis, E., Andersson, J., & Serletis, A. (2017). Electricity prices, large-scale renewable integration, and policy implications. *Energy Policy*, *101*, 550–560. https://doi.org/10.1016/j.enpol.2016.11.014

Lackner, K. S., Brennan, S., Matter, J. M., Alissa Park, A. H., Wright, A., & Van Der Zwaan, B. (2012). The urgency of the development of CO_2 capture from ambient air. *Proceedings of the National Academy of Sciences*, *33*(109), 13,156–13,162.

Lozanovski, A., Gebald, C., Brandstetter, C. P., Lindner, J. P., & Albrecht, S. (2014). Direct Air Capture of CO_2, University of Stuttgart and Climeworks. https://oc1.mainbase.ch/index.php/s/1aCEkJp0n3kjwxP#pdfviewer (accessed on August 9th, 2018), Archived at, http://www.webcitation.org/71XYlCFsS on August 9th, 2018.

Minx, J. C., Lamb, W. F., Callaghan, M. W., Bornmann, L., & Fuss, S. (2017). Fast growing research on negative emissions. *Environmental Research Letters*, *12*(3), 035007. https://doi.org/10.1088/1748-9326/aa5ee5

Minx, J. C., Lamb, W. F., Callaghan, M. W., Fuss, S., Hilaire, J., Creutzig, F., et al. (2018). Negative emissions—Part 1: Research landscape and synthesis. *Environmental Research Letters*, *13*(6), 063001. https://doi.org/10.1088/1748-9326/aabf9b

Peters, G. P., Andrew, R. M., Canadell, J. G., Fuss, S., Jackson, R. B., Korsbakken, J., et al. (2017). Key indicators to track current progress and future ambition of the Paris Agreement. *Nature Climate Change*, *7*(1), 118–122. https://doi.org/10.1038/nclimate3202

Pfenninger, S., Gauché, P., Lilliestam, J., Damerau, K., Wagner, F., & Patt, A. (2014). Potential for concentrating solar power to provide baseload and dispatchable power. *Nature Climate Change*, *4*(8), 689–692. https://doi.org/10.1038/nclimate2276

Pfenninger, S., & Staffell, fPeters I. (2016). Long-term patterns of European PV output using 30 years of validated hourly reanalysis and satellite data. *Energy*, *114*, 1251–1265. https://doi.org/10.1016/j.energy.2016.08.060

Rockström, J., Gaffney, O., Rogelj, J., Meinshausen, M., Nakicenovic, N., & Schellnhuber, H. J. (2017). A roadmap for rapid decarbonization. *Science*, *355*(6331), 1269–1271. https://doi.org/10.1126/science.aah3443

Rodriguez, R. A., Becker, S., Andresen, G. B., Heide, D., & Greiner, M. (2014). Transmission needs across a fully renewable European power system. *Renewable Energy*, *63*, 467–476. https://doi.org/10.1016/j.renene.2013.10.005

Schäfer, B., Beck, C., Aihara, K., Witthaut, D., & Timme, M. (2018). Non-Gaussian power grid frequency fluctuations characterized by Lévy-stable laws and superstatistics. *Nature*, *3*(2), 119–126. https://doi.org/10.1038/s41560-017-0058-z

Schleussner, C.-F., Rogelj, J., Schaeffer, M., Lissner, T., Licker, R., Fischer, E. M., et al. (2016). Science and policy characteristics of the Paris Agreement temperature goal. *Nature Climate Change*, *6*(9), 827–835. https://doi.org/10.1038/nclimate3096

Smith, P., Davis, S. J., Creutzig, F., Fuss, S., Minx, J., Gabrielle, B., et al. (2015). Biophysical and economic limits to negative CO_2 emissions. *Nature Climate Change*, *6*(1), 42–50. https://doi.org/10.1038/nclimate2870

Socolow, R., Desmond, M., Aines, R., Blackstock, J., Bolland, O., Kaarsberg, T., et al. (2011). Direct air capture of CO_2 with chemicals: A technology assessment for the APS Panel on Public Affairs (Tech. rep.). American Physical Society.

Staffell, I., & Pfenninger, S. (2016). Using bias-corrected reanalysis to simulate current and future wind power output. *Energy*, *114*, 1224–1239. https://doi.org/10.1016/j.energy.2016.08.068

van Vuuren, D. P., Hof, A. F., van Sluisveld, M. A., & Riahi, K. (2017). Open discussion of negative emissions is urgently needed. *Nature Energy*, *2*(12), 902–904. https://doi.org/10.1038/s41560-017-0055-2

van Vuuren, D. P., Stehfest, E., Gernaat, D. E. H. J., van den Berg, M., Bijl, D. L., de Boer, H. S., et al. (2018). Alternative pathways to the 1.5°C target reduce the need for negative emission technologies. *Nature Climate Change*, *8*(5), 391–397. https://doi.org/10.1038/s41558-018-0119-8

Welder, L., Ryberg, D., Kotzur, L., Grube, T., Robinius, M., & Stolten, D. (2018). Spatio-temporal optimization of a future energy system for power-to-hydrogen applications in Germany. *Energy*, *158*, 1130–1149. https://doi.org/10.1016/j.energy.2018.05.059

Wohland, J., Reyers, M., Maerker, C., & Witthaut, D. (2018). Natural wind variability triggered drop in German redispatch volume and costs from 2015 to 2016. *PLOS ONE*, *13*(1), e0190707. https://doi.org/10.1371/journal.pone.0190707