Earth's Future

Supporting Information for

A Comprehensive Assessment of Carbon Dioxide Removal Options for Germany

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Additional Supporting Information (Files uploaded separately)

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Introduction

The supplementary information follows the structure of the manuscript and gives additional details for the selected sections of the manuscript.

Text S1.

SI for section 2.1.4 Biological CDR options

In Wadden Sea salt marshes, a large fraction of the long-term preserved organic matter originate from marine-derived allochthonous sources accounting for more than 70% (Mueller et al., 2019). In contrast new data from the German Baltic Sea coast indicate that about 80% of the sediment blue carbon in these seagrass meadows is autochtonous (Stevenson et al., 2022). Importantly, restored meadows of *Zostera marina* regain their full potential approximately two years after planting (Lange et al., 2022). However, it must also be mentioned that seagrass meadows in the Wadden Sea can store significantly less carbon than salt marshes or seagrass meadows in other regions. Salt marshes occur naturally along the German Wadden Sea coast on an area of about 23,250 ha. The Wadden Sea salt marshes vegetation consists of a variety of herbs, grasses or low shrubs, and includes 3 distinct habitats; *Spartina* swards, *Salicornia* colonized mud and sand and Atlantic salt meadows (Esselink et al., 2017.)

Test S2.

SI for section 3.4 Economic assessment

The economic assessment consists of a number of different cost categories applied to the CDR options. It is based on quantitative data (e.g. in the area of market costs) as well as on qualitative assessments (e.g. with respect to transaction costs or investment barriers).

Often existing data is simply ambiguous, inadequate for a classification of the specific CDR option. Rather, based on the data available in the literature, it is possible to provide some general indication on possible cost ranges.

Marginal CO_2 removal costs tend to be lower for biological options (C1.1 are mostly green in Figure 2), sometimes even negative costs are indicated, as e.g. for cover crops -51 to 113 € per tCO_2 are stated (Fuss et al., 2018). The costs for peatland rewetting are assumed to be pretty low (10-15€/tCO_2, Couwenberg and Michaelis, 2015) while afforestation of croplands shows a very wide range in cost estimates (0-271€/tCO_2, Fuss et al., 2018). However, the marginal removal costs of biological options are highly side specific and thus cannot simply be transferred to the German context. This of course also translates into biomass based hybrid options. In general, chemical and hybrid options are characterized by higher marginal removal costs, e.g. 57-79 €/tCO_2 for biomass combustion CHP (Kearns et al., 2021), 139-313 €/tCO_2 for biogas-based options (IEAGHG, 2013), 150-177 €/tCO_2 for ERW (Beerling et al., 2020; Strefler et al., 2018), and 250 to 800 €/tCO_2 for DACC options (Heß et al., 2020) as they usually rely on technological equipment and recurring costs for inputs (energy, feedstock etc.). However, these features also offer potential for future cost reductions by further technological progress and economies of scale. Moreover, part of the costs may also be covered by revenues coming from sales of jointly produced goods, e.g. heat and electricity produced by BECC. In the evaluated CDR options, cost reduction potential by technological progress seems to be partially limited. In case of BECC higher potential is seen rather on the CO_2 capture side, than on the bioenergy generation side, as the latter one is delivered by mature technologies (e.g. combustion, pyrolysis). However, for some options cost reductions of scaling up operations (economies of scale) are expected to be quite significant, especially in the case of DACC where mass production of installations is likely to reduce its cost to an estimated ca. 50 €/tCO_2 in 2050 (Heß et al., 2020). In comparison, biological options can be expected to bear a lower potential for future cost reductions by technological progress and economies of scale.

Private transactions costs, e.g. for using relevant markets, setting up necessary contracts and complying with regulations, tend to be moderate to high for most of the CDR options. For chemical and hybrid options transaction costs for the erection of plants as well as for establishing supply chains/markets for inputs and outputs play a major role. For biological options often the high number of actors involved drives the transaction costs if new regulations have to be complied with and new markets need to be used, which is partially caused by the scattered ownership of private forest and agricultural land in Germany. The same applies e.g. to decentralized DACC which includes a high number of actors when applied on a larger scale as well as a larger number of relevant regulations.

The potential for increases in domestic value added provided by the deployment of the CDR options seems rather limited. This is due to little value added potential in general (as e.g. in the case of cover crops or the management of (existing) seagrass meadows) or the fact that the manufacturing and/or installation of equipment is (partially) done by companies from abroad (which might apply e.g. for DACC and BECC options).

An important barrier to investments in the CDR options can be caused by the expectation of a high amount of sunk costs in case the investment fails. This risk increases with the capital intensity of the CDR option (i.e. a high share of capital cost in the total cost of the measure), the specificity of the investment (i.e. the financial loss when assets would be applied for other purposes than the envisaged CDR option) as well as with the risks of the expected revenues. Due to low investment needs, biological options tend to possess a rather low capital intensity while hybrid and chemical options that require the erection of technical facilities come along with rather high capital intensity. However, as DACC appliances show high operating cost (due to their high energy consumption) their capital intensity tends to be lower compared to BECC options. Meanwhile, they show a very high specificity of investment, since the technical facilities can barely be used for other purposes and hence would be a stranded investment if DACC turns out to have no economic viability. The same applies to the equipment of existing bioenergy plants with carbon capturing facilities. Biomass-to-liquid plants could switch to the production of other gases for industrial use which makes their investment less specific than those of other BECC options. Since for biological options the carbon is often fixed in (marketable) biomass, selling off the biomass if the CDR case fails remains an option and reduces the specificity of the investment. The assessment of the revenue risk is challenged by the fact that many of the CDR options do not generate CDR related revenues (as e.g. seagrass meadows) or are not established yet. Thus, the institutional setting of a potential revenue scheme is unclear by now (e.g. DACC or ERW), which of course puts a high revenue risk on these options from today's perspective. The revenue risk is low for options that are remunerated for climate protection contributions by a fixed payment scheme such as the EU’s common agricultural policy (which applies to cover crops and afforestation on agricultural land). The revenue risk of BECC options usually seems to be moderate as technology-related risks are rather low due to the high maturity of these technologies, however, their revenue partially is dependent on the development of the EU emission trading scheme which has shown a high volatility in the past and moreover is subject to political discretion, putting a certain risk on the revenues of these facilities. In the case of macroalgae as a feedstock the revenue risk can be assumed to be higher since failing algae yields in Germany (e.g. due to pests or technical challenges) can barely be substituted as established markets are missing.

Data Set S1.

Summary tables including supporting information to Figures 1 to 3 from the main manuscript. File uploaded separately (name: ds01).

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