ENVIRONMENTAL RESEARCH
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To cite this article: Freia Harzendorf *et al* 2024 *Environ. Res. Lett.* **19** 111009

ENVIRONMENTAL RESEARCH
LETTERS

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RECEIVED
28 May 2024

REVISED
2 September 2024

ACCEPTED FOR PUBLICATION
12 September 2024

PUBLISHED
4 October 2024

PERSPECTIVE

Criteria for effective site selection of direct air capture and storage projects

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Keywords: DACS site assessment, carbon dioxide removal, stakeholder analysis, multi-factor impact assessment, negative emission technologies, legal framework, DACS-scale-up

Supplementary material for this article is available online

1. Introduction

The recent report by the Intergovernmental Panel on Climate Change [1] places significant emphasis on the requirement for carbon dioxide removal (CDR) to reach climate goals. A promising solution is direct air capture (DAC) coupled with geological storage of CO_2 (DACS), which is imperative for bolstering defossilization endeavors. In the most auspicious scenario DACS has the potential to remove up to 339 Gt CO_2 between 2020 and 2100, aligning with the Paris Agreement targets [2]. While technically feasible, DACS still requires significant deployment, with just 27 in some instances (pilot) plants currently operational capturing a limited amount of CO_2 annually [3].

To effectively scale-up DACS, careful consideration of suitable plant locations is crucial for successful scaling. Recent publications have explored site-specific technical criteria such as renewable energy potential, geological CO_2 storage capacity, existing CO_2 transport infrastructure, land and water consumption as well as the influence of climatic conditions [4–11].

While these factors are important, it is essential to consider a broader range of indicators, including socioeconomic factors, sustainability assessments, legal frameworks, and impacts on the national economy. Suboptimal outcomes have been observed in many large-scale projects due to the neglect of these non-technical factors. One example is the failure of the Desertec project which showed how inter alia overlooking non-technical factors can lead to project failure [12–14].

Recognizing this, we propose an interdisciplinary approach that ascertains DACS site suitability by integrating technical, economic, sociopolitical, legal, and environmental factors. Moreover, the paper explores the intersection of law and policy instruments, identifying specific policies and regulations that can facilitate the implementation of these criteria for setting up future DACS projects. By doing so, this paper aims to guide micro- and macroeconomic decision-making processes related to DACS scale-up and roll-out, enabling governments to integrate DACS technology into climate strategies successfully and investors to identify productive business opportunities.

2. Key criteria for evaluating DACS sites

In the following, we present essential criteria for conducting a multi-criteria based DACS project site assessment. For this, we assume that both DAC technology and underground CO_2 storage technology are already technically feasible. These criteria are designed to assist project developers in selecting an optimal site for implementing a DACS plant to achieve CDR. The project developer's perspective is chosen because they should ideally consider the perspectives of all relevant stakeholders in their decision-making process. The specific conditions of each site will determine the appropriate DAC technology, storage medium, and project size, such as capacity. When compiling these criteria, stakeholders who may be affected by or have a role in DACS implementation were considered. Eleven distinct stakeholder groups were identified, and their potential involvement in the siting of DACS was evaluated (please compare [15]). A comprehensive list of 73 distinct criteria for DACS site assessment is developed and provided on [15]. This compilation was based on an extensive review of literature and input from experts in various disciplines, ensuring the inclusion of diverse stakeholder perspectives. It is important to note that while this list expands upon existing academic and policy literature, it may not be exhaustive it is furthermore not possible to always differentiate between the criteria clearly as they impact each other. Figure 1 provides an aggregated version of the criteria that might be considered when selecting potential DACS sites. These key criteria are divided into five main groups, and the respective numbers in the full list provided in [15] are indicated in brackets in figure 1.

In '*Category 1*', technical facets related to capture, transportation, storage, and availability of resources decide the site of the project. '*Category 2*' encompasses economic aspects, which include carbon pricing and market dynamics. Social, organizational, and normative elements, for instance, stability in governance and legal certainty are evaluated in '*Category 3*'. 'Category 4' reviews potential harm to the environment, changes in land use and unintended impacts on air quality, and climate. 'Category 5' reflects upon local conditions, societal perception, and effective strategies for stakeholder engagement.

The next section discusses how individual criteria may be particularly applicable to certain stakeholders and specific decisions.

3. Hypothetical site assessment for DACS

The importance of individual criteria can vary depending on the perspective of stakeholders. To demonstrate this, two hypothetical instances are presented to emphasize the importance of key criteria. In Instance A, a government of a medium-sized nation in terms of territory with densely populated regions, strong economic growth, and ambitious climate goals must determine how to integrate DACS technology into its climate strategy and whether to prioritize domestic or international implementation. The following criteria (please compare the numbers in [15]) may be of utmost importance in this decision-making process. From the 'Climate, Energy, and Infrastructure Requirements' category, the 'availability of renewable energy' (criteria 2–4) is crucial due to the limited space for domestic implementation. Furthermore, assuring good 'performance' of DAC is vital to this case (criteria 1). From the 'Financial and Economic Considerations' the government might prioritize sites that maximize domestic economic benefits (criteria 34) or have the best cost-benefit from a welfare perspective (criteria 33). In terms of 'Political, Legal and Institutional Readiness', the government could focus on criteria such as legal readiness (criteria 62), functioning administrative structures (criteria 63) and human rights compliance (criteria 64), as well as political support and existing international cooperation for the implementation of DACS. From 'Environmental Factors and Climate Impact', criteria regarding the net reduction in global warming (criteria 65) and preventing trade-offs in other environmental impacts (criteria 36–38, 66–71) in densely populated areas might be vital. Lastly, in relation to 'Public Attitudes, Perception, and Acceptance', criteria focusing on risk and benefit perceptions (criteria 41–46), communication strategies (criteria 49), increasing trust (criteria 50–52) and climate change awareness (criteria 56–57) could be prioritized.

In Instance B, a global investor is seeking new business opportunities and intends to maximize revenue. The following criteria might be paramount to this investor's decision-making. From the 'Climate, Energy, and Infrastructure Requirements' category, the availability of infrastructure or planned development at potential project sites (criteria 7 and 8) is vital for successful implementation as well as the 'availability of renewable energy' (criteria 2–4). From 'Financial and Economic Considerations', criteria relevant to market potential, returns on investment, and the profitability of chosen DACS projects may be prioritized (criteria 18–31, for example). In terms of 'Political, Legal and Institutional Readiness', the investor could focus on criteria that promise an optimal cost-benefit ratio and low investment risk, such as existing economic incentive schemes (criteria 60), a functioning legal system (criteria 61) that provides legal certainty and effective administrative structures (criteria 63). Within 'Environmental Factors and Climate Impact', environmental criteria related to dynamics of the carbon market and regulatory compliance also including other environmental impacts might be prioritized. From 'Public Attitudes, Perception, and Acceptance', focus on risk and benefit perception (criteria 41–46), communication and trust building (criteria 49–51), communities with favorable demographics (criteria 52–55) and emphasis on renewables (criteria 58–59) are key to ensure a positive reception and market potential for the projects of the investor.

These examples demonstrate how different stakeholders and decision-making contexts prioritize various factors within the multi-factor criteria set for DACS siting. The decision-making process involves multiple criteria, and the significance of each one can differ depending on the stakeholders' roles and the specific goals at hand. This variation can lead to inherent conflicts during site selection. By using the key criteria set, legislators can better anticipate the interests of relevant stakeholders, establish

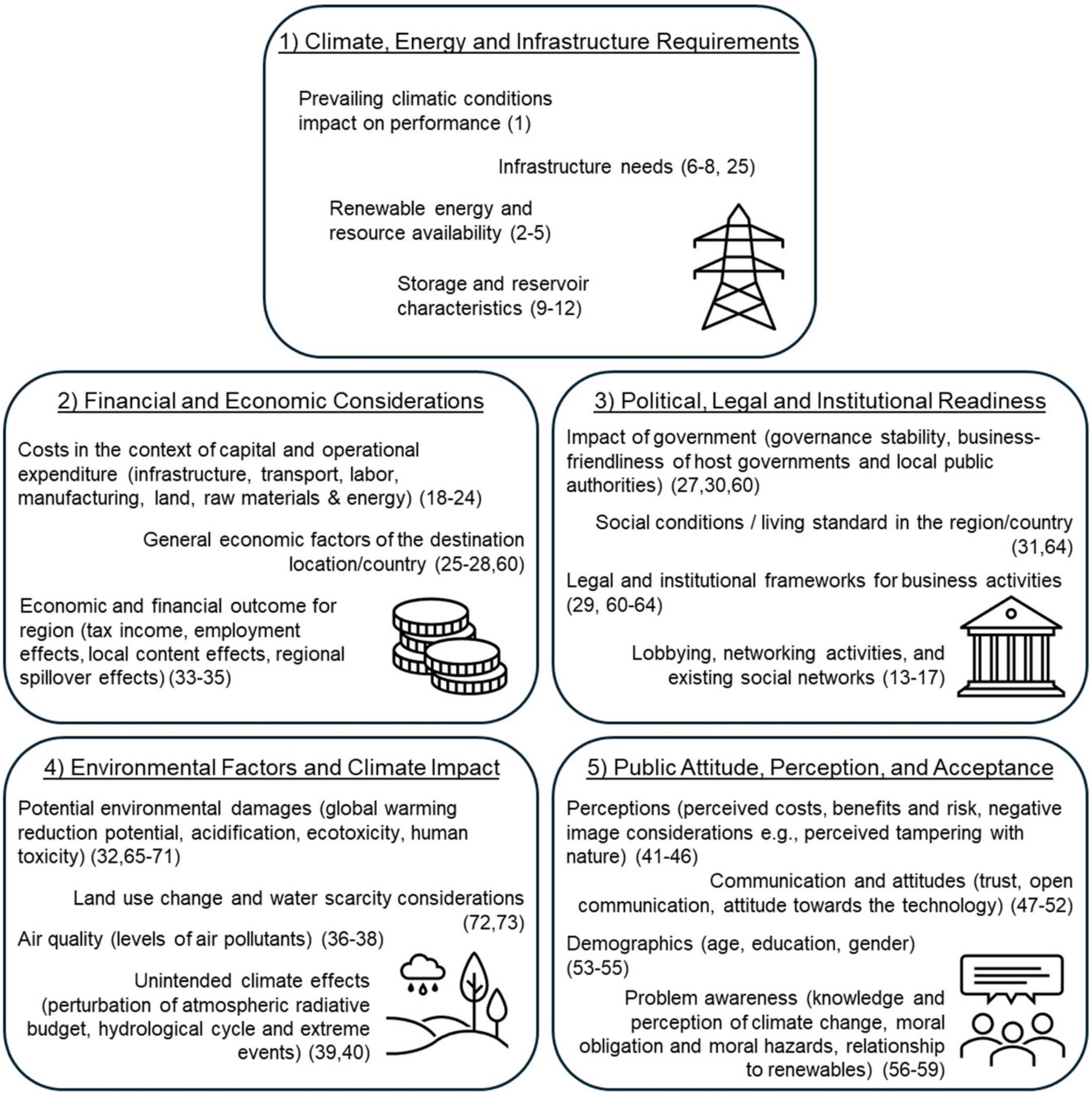

Figure 1. Direct air capture and storage key criteria set with five aggregated categories and the respective criteria in brackets (*for the full list with respective criteria numbers please refer to [15]).

appropriate incentives, and avoid imposing disincentives. This proactive approach not only helps prevent conflicts but also provides clear pathways for resolving any disagreements that may arise. The section below explores the possibilities of incorporating these multi-factor criteria set into laws and regulations.

The development of weighting schemes for different stakeholder in specific decision contexts is not part of this perspective and remains for future research.

4. Regulatory framework for DACS: incorporating multi-factor siting criteria

The following political and legal actions can contribute to facilitating the rapid and large-scale deployment of DACS, particularly when informed by the developed key criteria setmulti-factor criteria set for siting.

General political and legal commitments for DACS. Governments can adopt policy strategies and plans that articulate their view on the role of CDR in national climate policies. Setting quantitative targets demonstrates a country's commitment to utilize CDR and provides a framework for assessing potential market options for investors.

Spatial governance promoting optimal siting. Integrating the assessment criteria into spatial planning strategies can help to identify suitable areas for DACS deployment. Governments can strategically assess their DACS demands and suitability of territories using the key criteria, mapping out target or priority areas. This would involve coordinating with other sectoral spatial planning activities. If suitable areas within a country are limited, international negotiations for cooperative DACS development could be pursued.

Positive price signals. Governments can influence the economic viability of DACS operations by establishing price signals through financial support and market regulations. Applying consistent technical standards and institutional frameworks contributes to market credibility. Mandatory carbon trading systems, like the examples in the European Union and California [16], can be based on specific elements to incentivize DACS operations.

Specific laws governing the permission of DACS operations. The construction and operation of DACS plants require compliance with various laws and regulations, including planning and building regulations, water and soil conservation laws, and environmental impact assessments. Governments can expedite procedures by adopting clear permission requirements specific to DACS. Additionally, regulations surrounding the transport of CO_2 may need to be developed or harmonized to ensure efficient and safe transport. While specific regulation for DACS siting, construction, and operation may still be underdeveloped, many countries have made progress in adopting or developing legislation for CO_2 storage, which governs the storage of larger quantities of CO_2 [17, 18].

These political and legal actions, when guided by the key criteria for DACS siting, can create favorable conditions for rolling out DACS projects. Two additional factors must be taken into account: the timing of actions and the involvement of various stakeholders in the legislative process. If regulations are implemented too early or too late, they can create disincentives. For example, introducing financial incentives for investing in DACS before the energy system is sufficiently decarbonized could result in higher cumulative emissions. To prevent or address conflicts early on, it is crucial to establish stakeholder consultation processes. This engagement can help ensure that large-scale projects move forward without unnecessary delays or failures.

5. Conclusions and policy recommendations

The multi-factor criteria set and its hypothetical applications discussed in this perspective showed that a vast number of criteria have an impact on optimal DACS siting. It is therefore important to have the developed multi-factor siting criteria at hand when choosing a project's site and setting up political and legal conditions to facilitate the deployment of DACS. Several policy recommendations with a focus on siting can support the successful implementation of DACS and increase the attractiveness of a site for a DACS project. Firstly, explicit commitments to DACS should be outlined by governments. This can be achieved through the adoption of policy strategies that clearly articulate the role of CDR in national climate policies and the setting of quantifiable targets to attract potential investors. Robust spatial governance is necessary and may also include international negotiations for collaborative DACS development. Establishing legal frameworks specific to DACS operations is crucial. Governments should streamline processes by implementing DACS-specific permission requirements and consider harmonizing regulations surrounding CO_2 transport for a more efficient and safer transfer process. While this paper provides key criteria for DACS site assessment, future research could focus on the practical implementation of these criteria in real-life contexts including the development of weighting schemes. Analyzing barriers and potential solutions for wide-scale DACS adoption and studying socio-political dynamics and public sentiment towards DACS globally could provide valuable insights for more effective engagement strategies.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://doi.org/10.5281/zenodo.11372468.

Acknowledgment

This work was performed as part of the project 'A Comprehensive Approach to Harnessing the Innovation Potential of Direct Air Capture and Storage for Reaching CO2-Neutrality' (DACStorE), which is funded by the Initiative and Networking Fund of the Helmholtz Association (Grant Agreement Number KA2-HSC-12).

Declaration

During the preparation of this work the authors used OpenAI to enhance readability and for translation services. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

CrediT Statement

Freia Harzendorf: conceptualization, methodology, investigation, writing—original draft & editing, visualization, project administration, funding acquisition; **Till Markus**: conceptualization, methodology, investigation, writing—review, funding acquisition; **Andrew Ross**: conceptualization, methodology, investigation, writing—original draft; **Rodrigo Valencia Cotera**: investigation, writing—review; **Constanze Baust**: investigation; **Stefan Vögele**: methodology, investigation; **Domenico**

Taraborelli: methodology, investigation, writing—review, funding acquisition; **Petra Zapp**: methodology, investigation, writing—review, funding acquisition; **Vlassis A. Karydis:** investigation, writing—review, funding acquisition; **Paul Bowyer:** investigation; **Detlef Stolten**: funding acquisition

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