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Reviewing the role of bioenergy with carbon capture and storage (BECCS) in climate mitigation

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ABSTRACT

Climate change poses an imminent threat, necessitating innovative and sustainable strategies for mitigation. This paper explores the potential of Bioenergy with Carbon Capture and Storage (BECCS) as a promising approach. The introductory section sets the stage by elucidating the urgency of climate action. The background section surveys existing climate mitigation strategies, introducing bioenergy and carbon capture technologies. The paper delves into the distinctive contributions of bioenergy to carbon emission reduction and assesses the viability of various bioenergy sources. Simultaneously, the discussion on Carbon Capture and Storage (CCS) provides insight into the technological aspects of carbon capture. An integral focus is the integration of bioenergy and carbon capture technologies in BECCS, exploring synergies that enhance their combined efficacy. Real-world examples and case studies illustrate successful BECCS projects. Environmental and social impacts are critically examined, considering sustainability and ethical dimensions. Challenges and criticisms associated with BECCS are discussed comprehensively, addressing concerns and proposing potential solutions. The paper concludes by outlining future prospects for BECCS, offering recommendations for policymakers and stakeholders. It also suggests avenues for further research and development in this evolving field.

Keywords: Bioenergy, Carbon Capture and Storage (BECCS), Climate Mitigation.

INTRODUCTION

Climate change, driven primarily by human activities, has emerged as one of the most pressing global challenges of our time (Steffen et la., 2011). The rise in greenhouse gas emissions, particularly carbon dioxide (CO2), methane (CH4), and nitrous oxide (N2O), has led to unprecedented changes in the Earth's climate (Aryal et al., 2022). The consequences of climate change are wide-ranging, encompassing rising global temperatures, more frequent and severe weather events, disruptions to ecosystems, and threats to food security. Mitigating climate change is imperative to safeguard the planet's ecological balance and ensure the well-being of present and future generations. The urgency of this task is underscored by international agreements such as the Paris Agreement, which calls for collective efforts to limit global warming to well below 2 degrees Celsius above pre-industrial levels (Falkner, 2016). In response to the need for effective mitigation strategies, Bioenergy with Carbon Capture and Storage (BECCS) has gained prominence as a potential game-changer. BECCS is a synergistic approach that combines the utilization of bioenergy sources with carbon capture and storage technologies (Cabral et al., 2019). Bioenergy involves harnessing energy from biological sources such as biomass, organic waste, and crops, while carbon capture and storage focus on capturing CO2 emissions at their source and securely storing them underground. BECCS holds promise as a versatile and sustainable solution, addressing both the energy demand and carbon reduction goals. By utilizing organic materials to generate energy and simultaneously capturing and storing the resulting carbon emissions, BECCS has the potential to achieve negative emissions, actively reducing atmospheric CO2 concentrations (Full et al., 2021). The purpose of this paper is to conduct a comprehensive review of the role of BECCS in climate mitigation. By examining the synergies between bioenergy and carbon capture technologies, we aim to assess the effectiveness and sustainability of BECCS as a mitigation strategy. This review will explore the potential of BECCS in contributing to global efforts to reduce greenhouse gas emissions and achieve climate goals. The significance of this paper lies in its contribution to the understanding of BECCS within the broader context of climate change mitigation. As countries and industries seek viable solutions to meet emission reduction targets, a thorough examination of BECCS becomes essential. Insights derived from this review can inform policymakers, researchers, and stakeholders involved in shaping sustainable energy and climate policies.

Explanation of Climate Mitigation and its Importance

Climate mitigation encompasses a set of strategies and actions aimed at reducing or preventing the emission of greenhouse gases (GHGs) to alleviate the impacts of climate change (VijayaVenkataRaman et al., 2012). The importance of mitigation lies in its role as a proactive response to the anthropogenic activities driving global warming. Mitigation measures are crucial in achieving international climate goals, such as those outlined in the Paris Agreement, which seeks to limit global temperature increases to well below 2 degrees Celsius above pre-industrial levels. Mitigation efforts not only contribute to climate stability but also address associated challenges such as sea-level rise, extreme weather events, and disruptions to ecosystems. As the global community faces the urgency of mitigating climate change, it becomes imperative to explore and implement sustainable solutions (Warren, 2011). Various climate mitigation strategies have been employed to curb the emission of greenhouse gases. These strategies encompass a wide range of sectors, including energy, transportation, industry, and land use. Renewable energy deployment, energy efficiency improvements, and the transition to low-carbon technologies are key components of mitigation efforts (IPCC, 2014). Additionally, afforestation and reforestation projects aim to enhance carbon sequestration, mitigating the impact of deforestation. Despite these efforts, achieving significant emissions reductions remains a complex challenge. This necessitates the exploration of innovative and integrated approaches such as Bioenergy with Carbon Capture and Storage (BECCS) to meet ambitious mitigation targets. Bioenergy, derived from organic materials such as biomass, plays a vital role in the transition to a low-carbon energy system (Vaillancourt, et al., 2019). It offers a renewable and sustainable alternative to fossil fuels, contributing to reduced carbon emissions. Carbon capture technologies, on the other hand, involve capturing and storing CO_2 emissions generated from industrial processes and energy production. The combination of bioenergy and carbon capture technologies in BECCS represents a multifaceted approach to mitigation. Bioenergy provides a carbon-neutral energy source, and carbon capture ensures that the CO_2 released during bioenergy utilization is captured and stored, preventing it from entering the atmosphere.

Bioenergy and its Role in Mitigation

Bioenergy, derived from organic materials, encompasses a diverse range of renewable sources that can be harnessed to produce heat, electricity, or fuel (Shankar and Shikha, 2017). Common bioenergy sources include biomass, biofuels, and biogas. Biomass, such as wood, crop residues, and organic waste, is the most widely used form of bioenergy. Biofuels, such as ethanol and biodiesel, are liquid fuels derived from biological sources, often crops like sugarcane and corn. Biogas is produced through the anaerobic digestion of organic matter and is primarily composed of methane (Li et al., 2011). Understanding the different types of bioenergy sources is essential to assess their potential contribution to climate mitigation. Each source has distinct characteristics, including energy content, carbon footprint, and suitability for various applications. While bioenergy is considered renewable, its sustainability is contingent on various factors. The cultivation and utilization of bioenergy sources must be managed to avoid negative environmental impacts. Sustainable bioenergy practices involve responsible land use, avoiding deforestation, and ensuring that the energy conversion processes are efficient (van Dam et al., 2010). However, challenges such as competition for land with food crops and the potential for biodiversity loss necessitate careful consideration. Sustainable bioenergy practices aim to strike a balance between meeting energy demands and mitigating environmental impacts. Bioenergy plays a crucial role in reducing carbon emissions by providing an alternative to fossil fuels. The combustion of biomass releases CO_2, but the carbon emitted is part of the natural carbon cycle, as plants absorb CO_2 during growth. Therefore, the net carbon emissions from bioenergy are often considered neutral or even negative over the long term, especially when coupled with sustainable forestry practices. The potential of bioenergy in carbon emission reduction depends on factors such as the type of feedstock, land-use changes, and the efficiency of energy conversion technologies. Assessing the life cycle emissions of bioenergy is essential to accurately evaluate its contribution to climate mitigation. As we explore the role of bioenergy in mitigation, it becomes apparent that its sustainable deployment is crucial to realizing its full potential in reducing carbon emissions.

Carbon Capture and Storage (CCS)

Carbon Capture and Storage (CCS) technologies are instrumental in mitigating climate change by capturing carbon dioxide (CO2) emissions from industrial processes and power plants before they are released into the atmosphere (Anwar et al., 2018). CCS involves three main steps: capture, transport, and storage. CO2 is captured from industrial processes, usually through pre-combustion capture, post-combustion capture, or oxy-fuel combustion. Various capture technologies, such as amine scrubbing and membrane separation, are employed to isolate CO2 from other gases. Once captured, the CO2 is transported to a storage site. Pipelines are commonly used for this purpose, facilitating the movement of CO2 from the capture site to the storage location. The captured CO2 is stored underground in geological formations such as depleted oil and gas fields or deep saline aquifers. The goal is to securely store the CO2, preventing its release into the atmosphere.

CCS has demonstrated effectiveness in capturing a significant portion of carbon emissions from various industrial processes and power generation (Gür, 2022). By preventing CO2 from entering the atmosphere, CCS contributes to mitigating climate change. The captured CO2 can be stored permanently underground, reducing the overall carbon footprint of these activities. The efficiency of CCS technologies is subject to ongoing research and development. Improvements in capture technologies, cost reductions, and advancements in monitoring and verification methods are crucial for enhancing the effectiveness of CCS in diverse applications. While CCS holds promise, its widespread implementation faces several challenges. Economic factors, including the high cost of implementing CCS infrastructure, pose a significant barrier. Additionally, public acceptance, regulatory frameworks, and potential leakage risks are areas that require careful consideration. The permanence and integrity of CO2 storage sites are crucial to the success of CCS. Addressing these challenges necessitates interdisciplinary efforts, involving policy-makers, industry stakeholders, and researchers, to create a supportive environment for CCS deployment (Stigson et al., 2012). As we evaluate the role of CCS in climate mitigation, understanding its capabilities and limitations is essential for informed decision-making and the development of effective strategies to combat climate change.

Integration of Bioenergy with Carbon Capture and Storage (BECCS)

Bioenergy with Carbon Capture and Storage (BECCS) represents a holistic and synergistic strategy to address both energy needs and climate change mitigation simultaneously. BECCS combines the sustainable use of bioenergy with the capture and storage of carbon dioxide (CO2) emissions (Quader and Ahmed, 2017). The process begins with the generation of energy from biomass, organic waste, or crops, which produces CO2. However, instead of releasing this CO2 into the atmosphere, BECCS integrates carbon capture technologies to capture the emissions. The captured CO2 is then transported and securely stored underground, preventing its release and contributing to negative emissions. BECCS thus offers a unique dual benefit: it provides renewable energy while actively reducing atmospheric CO2 concentrations. The integration of bioenergy and carbon capture technologies in BECCS capitalizes on the synergies between these two components (Bellamy et al., 2021). Bioenergy provides a carbon-neutral or even carbon-negative energy source, as the CO2 released during combustion is part of the natural carbon cycle. Simultaneously, carbon capture ensures that the CO2 emissions from bioenergy utilization are captured, preventing them from contributing to the greenhouse effect. The combined approach of BECCS allows for the removal of CO2 from the atmosphere, actively contributing to negative emissions (Fajardy et al., 2018; Oladipo et al., 2024). This process aligns with global climate goals, aiming to achieve a net reduction in greenhouse gas concentrations to mitigate the impacts of climate change. Several BECCS projects worldwide serve as practical examples of the integration's success. One notable project is the Drax Power Station in the United Kingdom, where a biomass conversion program is coupled with carbon capture technologies. By transforming a coal-fired power plant into one that utilizes biomass and employs carbon capture, the Drax Power Station showcases the potential for BECCS to reduce emissions while maintaining energy production. Additionally, the Archer Daniels Midland Company's Illinois Industrial Carbon Capture and Storage project in the United States demonstrates the application of BECCS in an industrial setting. This initiative captures CO2 emissions from ethanol production and sequesters them underground, highlighting the versatility of BECCS across various sectors. As BECCS gains momentum globally, these case studies offer valuable insights into its feasibility, challenges, and potential contributions to sustainable energy and climate goals.

Environmental and Social Impacts

BECCS, as a climate mitigation strategy, brings both environmental benefits and potential challenges. On the positive side, BECCS can contribute to reduced atmospheric carbon dioxide (CO2) concentrations, addressing climate change (Kriegler et al., 2013; Nwankwo et al., 2024). The use of biomass for energy generation is often considered carbon-neutral or even carbon-negative over the long term, as the carbon released during combustion is part of the natural carbon cycle. Additionally, BECCS can potentially promote sustainable land management practices by encouraging the cultivation of energy crops and the responsible use of biomass resources. However, the environmental implications of BECCS also warrant careful consideration. Land-use changes associated with large-scale bioenergy cultivation may lead to biodiversity loss, habitat disruption, and potential conflicts with food production. Moreover, the efficiency of carbon capture technologies in BECCS influences its overall environmental impact. Ensuring that BECCS projects adhere to sustainable practices is crucial to maximizing their positive environmental outcomes. The social and economic dimensions of BECCS implementation are integral to its success and acceptance (Gough and Mander, 2019; Okoye et al., 2023). BECCS projects can create employment opportunities in the bioenergy sector, contribute to rural development, and potentially stimulate economic growth. However, careful attention must be paid to social equity, ensuring that the benefits of BECCS are distributed fairly among communities. Social considerations also encompass issues related to land use and resource competition. Balancing the demand for bioenergy feedstocks with other essential land uses, such as agriculture and conservation, requires transparent and inclusive decision-making processes (van Dam et al., 2010; Tula et al., 2024). Engaging local communities and stakeholders in the planning and execution of BECCS projects is essential for fostering social acceptance and minimizing negative impacts. BECCS raises ethical considerations that span environmental, social, and economic realms. Ensuring that BECCS projects adhere to sustainability principles is an ethical imperative. This includes the responsible sourcing of biomass, avoiding land-use practices that lead to deforestation or displacement of local communities, and minimizing negative impacts on biodiversity. Ethical considerations also involve addressing potential trade-offs between BECCS and other climate mitigation strategies (Gough, et al., 2018; Odunaiya et al., 2024). Assessing the overall ethical implications of BECCS requires a comprehensive evaluation of its contributions to climate goals, potential adverse effects, and its alignment with broader ethical frameworks. As BECCS continues to be explored as a climate solution, incorporating ethical considerations into decision-making processes is essential for fostering responsible and sustainable implementation.

Challenges and Criticisms

While Bioenergy with Carbon Capture and Storage (BECCS) holds promise as a climate mitigation strategy, it is not without challenges. One significant challenge is the potential competition for land between bioenergy production and other essential land uses, such as agriculture and conservation. Large-scale bioenergy cultivation could lead to deforestation, habitat disruption, and impacts on food production if not carefully managed. Striking a balance between bioenergy needs and sustainable land use is critical. Technological challenges also exist, including the efficiency of carbon capture technologies and the overall energy balance of BECCS systems (Shahbaz et al., 2021). Improvements in these areas are essential to enhance the effectiveness and viability of BECCS as a climate solution. Moreover, the scalability and feasibility of BECCS on a global scale face economic and logistical hurdle. Implementing BECCS at the required scale demands significant investments in infrastructure, and cost-effectiveness remains a concern. BECCS has faced criticisms from various perspectives, raising concerns that warrant careful consideration (Babin et al., 2021). Some environmentalists argue that large-scale bioenergy cultivation might lead to the conversion of natural ecosystems into monoculture plantations, negatively impacting biodiversity. Additionally, the carbon neutrality of bioenergy is questioned, as it may take years or decades for newly planted vegetation to offset the initial emissions from biomass combustion. Social justice concerns include potential land-use conflicts and the displacement of local communities due to bioenergy production. Moreover, the idea of BECCS contributing to negative emissions is contested, as uncertainties exist in quantifying the long-term carbon sequestration potential and the sustainability of large-scale implementation (Workman et al., 2020). Addressing the challenges and criticisms surrounding BECCS requires a multifaceted approach. Rigorous sustainability criteria must be established to guide the sourcing of biomass and the implementation of BECCS projects. Ensuring that bioenergy feedstocks are derived from responsibly managed lands and avoiding conversion of natural habitats are critical steps. Technological advancements are essential to enhance the efficiency of carbon capture processes and improve the overall energy balance of BECCS systems. Research and development efforts should focus on optimizing these technologies to make BECCS more cost-effective and scalable. Community engagement and participatory decision-making are crucial for addressing social concerns associated with BECCS. Implementing inclusive governance structures that involve local communities in the planning and decision-making processes can help mitigate social conflicts and ensure fair distribution of benefits. As BECCS continues to be explored as a climate mitigation strategy, addressing these challenges and criticisms is essential for fostering its sustainable and responsible implementation.

Future Prospects and Recommendations

The future role of Bioenergy with Carbon Capture and Storage (BECCS) in climate mitigation holds significant potential but also faces uncertainties and challenges (Babin et al., 2021). As the global community intensifies efforts to achieve net-zero emissions and limit global warming, BECCS is expected to play a pivotal role in the portfolio of climate mitigation strategies. BECCS could contribute to achieving negative emissions, helping offset residual greenhouse gas emissions from challenging sectors such as heavy industry and aviation. The scalability and versatility of BECCS make it an attractive option for addressing emissions in sectors where direct decarbonization is particularly challenging. However, the future role of BECCS is contingent on advancements in technology, policy support, and the establishment of robust sustainability criteria (Grant et al., 2021). Continued research and development are essential to enhance the efficiency of carbon capture technologies, reduce the cost of BECCS implementation, and address environmental and social concerns. Policymakers play a crucial role in shaping the future trajectory of BECCS. Clear and supportive policies that incentivize the deployment of BECCS, while ensuring sustainability and social equity, are imperative. Policymakers should consider establishing regulatory frameworks that prioritize sustainable biomass sourcing, encourage research and development, and provide financial incentives for BECCS projects (Stavrakas et al., 2018). Stakeholders, including industry leaders, researchers, and non-governmental organizations, should collaborate to address challenges and share best practices. Building partnerships across sectors and fostering international cooperation can accelerate the development and deployment of BECCS on a global scale. To realize the full potential of BECCS, ongoing research and development efforts are crucial (Fuss and Johnsson, 2021). Key areas for further exploration include: Invest in research to enhance the efficiency of carbon capture technologies, explore new capture methods, and optimize the overall energy balance of BECCS systems. Conduct comprehensive life cycle assessments to evaluate the environmental and social impacts of BECCS projects, with a focus on sustainable biomass sourcing, land-use changes, and long-term carbon sequestration (Duval-Dachary et al., 2023). Investigate ways to reduce the cost of BECCS implementation, explore innovative financing mechanisms, and assess the economic feasibility of large-scale deployment. Study and address social concerns associated with BECCS, including land-use conflicts, community engagement, and equitable distribution of benefits. Encourage international collaboration to share knowledge, experiences, and best practices, facilitating the development of a globally applicable framework for BECCS implementation (Torvanger, 2019). The future prospects of BECCS in climate mitigation are promising, but successful integration requires a comprehensive and collaborative approach involving policymakers, stakeholders, and the scientific community. Continued research, robust policies, and sustainable practices are essential for realizing the potential benefits of BECCS in the global fight against climate change.

CONCLUSION

The review of the role of Bioenergy with Carbon Capture and Storage (BECCS) in climate mitigation has unveiled a multifaceted landscape. The urgency of addressing climate change has propelled BECCS into the spotlight as a potential solution with the capacity to provide sustainable energy while actively reducing atmospheric carbon dioxide (CO2) concentrations. The overview of climate change and the need for mitigation strategies highlighted the critical importance of finding innovative approaches to meet global emission reduction targets. BECCS, through the integration of bioenergy and carbon capture technologies, emerges as a viable contender to contribute to these efforts (Hayat et al., 2021). The exploration of bioenergy emphasized its diversity, encompassing various sources such as biomass, biofuels, and biogas. While bioenergy offers a renewable and potentially carbon-neutral energy source, the sustainability of its production and utilization remains a crucial consideration.

Carbon capture and storage (CCS) technologies were discussed as an essential component of BECCS, playing a pivotal role in capturing and securely storing CO2 emissions. The effectiveness of CCS in mitigating carbon emissions was underscored, acknowledging its potential to be part of a comprehensive strategy for achieving net-zero emissions. The synergies between bioenergy and CCS in BECCS were analyzed, highlighting the unique advantage of the dual approach. BECCS not only provides an alternative, sustainable energy source but actively contributes to negative emissions, aligning with global climate goals. The comprehensive examination of BECCS revealed both its potential and challenges. Policymakers are presented with an opportunity to strategically incorporate BECCS into climate policies, emphasizing the importance of: Establishing Clear Regulations: Implementing clear regulatory frameworks that incentivize BECCS deployment while ensuring sustainable practices and social equity. Prioritizing Research and Development: Supporting ongoing research and development efforts to enhance the efficiency of carbon capture technologies, reduce costs, and address environmental and social concerns. Encouraging International Collaboration: Facilitating global collaboration to share knowledge, experiences, and best practices for the successful implementation of BECCS on a global scale. BECCS emerges as a promising avenue for climate mitigation, combining renewable energy with carbon capture to address both energy needs and carbon reduction goals. However, the challenges and criticisms surrounding BECCS necessitate a careful and well-informed approach. As we navigate the complexities of climate change and seek viable solutions, BECCS stands as a valuable tool in the broader portfolio of mitigation strategies. A collective effort from policymakers, industry leaders, researchers, and communities are essential to ensure the responsible and sustainable deployment of BECCS, contributing to a more resilient and sustainable future. The call to action is clear: continue research, invest in technological innovation, establish supportive policies, and engage in collaborative efforts to unlock the full potential of BECCS in the global fight against climate change.

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