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Corresponding Author
Mushtaq Ahmad,
Department of Chemical Engineering, University of Engineering and Technology, Peshawar in pakistan
mushtaqahmad96268@gmail.com

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Bioenergy with Carbon Capture and Storage (BECCS): Case Study of Pakistan (2015-2024)

[1]Mushtaq Ahmad, [2]Basit Ali, [3]Muhammad Ilyas, [4]Shah Hamdani, [5]Aiman Sher and [6]Muhammad Yasir
[1-6]Department of Chemical Engineering, University of Engineering and Technology, Peshawar in pakistan

Abstract
Global climate goals can only be realized with increasing uptake of the Bioenergy with Carbon Capture and Storage (BECCS). This paper examines how beccs can be used in Pakistan: its potential, its progress and challenges (2015-2024). The country's biomass energy resources, its policy landscape, institutional framework and current carbon capture initiatives are assessed to determine the feasibility and readiness to deploy BECCS. Through a mixed method case study of BECCS in Pakistan, using a combination of policy analysis, energy production data and extensive expert interviews, the study finds that despite Pakistan boasting a considerable biomass potential, mainly in the form of agricultural residues, the level of implementation of BECCS remains very low because of technological, financial and institutional barriers. The study also points towards opportunities to integrate BECCS into Pakistan's climate policy in order to support its Nationally Determined Contributions (NDC). The study is key for stakeholders to develop BECCS in Pakistan and fits into wider debate on energy transitions in developing economies.

INTRODUCTION

Likewise, the gravity of threat to the future of our world with climate change has never been greater and with it the demand for bold-scalable, sustainable, low cost-solutions to reduce atmospheric carbon dioxide. Among myriad negative emission technologies (NETs), the one most widely discussed is Bioenergy with Carbon Capture and Storage (BECCS), in which renewable energy is produced and CO2 is removed from the atmosphere. Biomass energy with carbon capture and storage (BECCS) entails the utilization of organic material or biomass (e.g. plants, animals), as a fuel for energy production accompanied by permanent capture and storage of carbon emissions that result from its use. One of this process advantages is that it provides a renewable energy resource and also delivers so called negative emissions and this last one is fundamental to reach the global climate targets of the Paris Agreement. Pakistan like many other developing countries of the world faces a dual challenge of (i) minimizing the energy insecurity and (ii) limiting the adverse impacts of climate change. The country's energy sector depends on fossil fuels with heavy usage and growing population and rapid urbanization have been putting higher demand for energy. simultaneously, Pakistan is highly susceptible to climate change with higher temperatures, changing patterns of precipitation and extreme weather events. In the current context, BECCS is an opportunity of a kind and one which could offer the pathway to a low carbon future, but it also enhances energy resilience. Diversifying its energy mix, between 2015 and 2024 Pakistan promoted renewable energy sources such as solar, wind and biomass. Carbon capture technology is still in infancy. This study discusses the availability of biomass resources, current policy and institutional landscape, technological readiness of BECCS and barriers and opportunities of BECCS implementation in Pakistan to explore the potential of BECCS. The case study measures how far Pakistan can utilise BECCS in the specified time frame. In this thesis, the focus on the discourse around sustainable energy transition in developing countries is applied through an analysis of Pakistan's energy and environmental strategies through the last decade. Second, it aims to provide policymakers (and other stakeholders within industry and researchers that wish to use BECCS in national context for climate and energy policies and planning).

Specific Objectives:

- To assess the availability and utilization of biomass resources for bioenergy production in Pakistan.
- To evaluate the technological readiness and infrastructure for carbon capture and storage (CCS) in Pakistan.
- To examine the policy and institutional frameworks related to renewable energy, BECCS and climate change in the country.
- To identify the key barriers and opportunities for the implementation of negative emissions technologies, particularly BECCS, in Pakistan.
- To provide policy recommendations for integrating BECCS into Pakistan's national climate and energy strategies.

Research Questions:

- What is the current status of biomass availability and bioenergy production in Pakistan from 2015-2024?
- What is the level of technological and infrastructural development for carbon capture and storage (CCS) in Pakistan?
- How do existing energy policies and climate change strategies support or hinder the adoption of BECCS?
- What are the major challenges and opportunities for deploying BECCS as a negative emissions technology in the Pakistani context?
- How can BECCS contribute to sustainable development and the achievement of Pakistan's climate targets?

Research Gap: Empirical and case based research on BECCS in Pakistan shows there is a gap. Except for a few studies, studies have primarily focused on either biomass energy or CCS individually, with little integration of the two. In addition, local assessments typically use theoretical models rather than real world feasibility analysis and there is a demand for more grounded research which takes into account the distinct economic, political and environmental setting of Pakistan. This gap is attempted to be filled by analyzing BECCS potential in Pakistan over the decade, in detail.

Literature Review:

Introduction to BECCS and Global Context: Bioenergy with Carbon Capture and Storage (BECCS) is now understood as an essential part of negative emission strategies to limit warming to below 1.5°C as discussed by the IPCC[1]. Capturing and storing CO2 emissions from biomass based energy production is called the BECCS process which makes CO2 removal from atmosphere effective. BECCS has been positioned as a promising technology, because of its dual roles of providing renewable energy and facilitating carbon dioxide removal (CDR) through various global assessments[2,3]. Some developed countries, for example the United States, United Kingdom and Sweden, have taken an early lead in piloting BECCS

projects against a backdrop of long term climate targets Rogelj[4]. But in Pakistan, for example, a developing country, the development is not explored this much. According to Gough and Vaughan[5], BECCS has the potential to contribute in low income countries because of available bio-mass but there are several economic, technical and policy challenges that are challenging its implementation.

Biomass Energy Potential in Pakistan: Biomass energy has a potential in Pakistan which is an agrarian economy. The country produces annual agricultural residues approximately 50 million ton per annum which include wheat straw, rice husks, cotton stalks and sugarcane bagasse AEDB[6]. Efficient harnessing of these resources could make a sustainable base for bioenergy production. Khan[7] and Malik and Farooq[8] also noted that the country has been inefficient in using the bioenergy sector, owing to the unavailability of infrastructure, investment and proper policy guidelines. Yet a handful of biomass projects have come up in Pakistan during the 2015-2024 period and are largely from the sugar industry where bagasse is used for cogeneration. Nevertheless, because these projects are run without integrated carbon capture components, their climate mitigation potential is restricted Ahmed[9]. The consensus among researchers is that integrating CCS with such biomass initiatives might profoundly improve Pakistan's carbon balance-especially when looking at rising energy demand in light of Pakistan's vulnerability to climate.

Carbon Capture and Storage (CCS) in Developing Countries: Carbon Capture and Storage (CCS) has been extensively studied in the global North, but has not yet been applied in developing countries. In the South Asian context, high costs of deployment, absence of regulatory framework and inadequate technical expertise to put CCS in place IEA[10]. Recent studies Hassan[11], Saeed[12] indicate that though, theoretically, geological CO2 storage in depleted oil and gas fields may be suitable for Pakistan, practically the deployment is limited because the policy has been inactive and there are no pilot projects. In addition, little public or private sector investments exist for research and development in relation to CCS. The implementation of CCS as part of BECCS is highly uncertain without dedicated funding, capacity building and international cooperation. However, many writers emphasize how international climate finance and technology transfer mechanisms, like those under the Green Climate Fund (GCF) UNFCCC[13] could aid Pakistan in the justification of CCS feasibility.

Policy Landscape and Institutional Barriers: During 2015-2024 Pakistan has developed renewables in its energy policy framework but carbon management is largely absent. Biomass energy is promoted but provisions on carbon capture are not concrete in the Alternative and Renewable Energy Policy 2019. Pakistan's Nationally Determined Contributions (NDCs) under the Paris Agreement also commit to reducing emissions by 50% by 2030, in the presence of international support, but do not explicitly involve BECCS or CCS in the mitigation pathway GoP[14]. Rauf[15-17] further explains that institutional fragmentation, fragmented jurisdictions and lack of coordination between energy and environment ministries create barriers to navigate and therefore weaken the implementation potential of such advanced technologies as BECCS. Moreover, the lack of specific incentives (or regulatory frameworks) such as carbon pricing or emission reduction, diminishes the economic attractiveness of these projects.

Research Design: The study uses a mixed methods case study approach to analyze the potential, implementation and challenges of Bioenergy with Carbon Capture and Storage (BECCS) in Pakistan during the year 2015-2024 through the application of both qualitative and quantitative analysis. Due to the multidisciplinary nature of BECCS (at the crossroads of environmental science, energy policy and economics), Qualitative Analysis will be used to evaluate policy documents, expert opinions and institutional frameworks. Quantitative Analysis will be done of biomass energy production data, carbon emissions statistics and technology readiness indicators.

Data Sample and Time Frame: This study is confined to a 10 year period (2015-2024), synchronized with Pakistan's renewable energy transition and updated Nationally Determined Contributions (NDCs) to the Paris Accord.

Sample of Data:

- **Biomass Energy Projects:** Sugarcane bagasse cogeneration plants, rice husk units, and agricultural waste-to-energy initiatives.
- Data Collection Methods
- **Secondary Data Collection**
- Government Reports AEDB annual reports, NDC updates (GoP), Energy Yearbooks.
- International Sources: IPCC, IEA, UNFCCC, IRENA publications on BECCS and CCS,
- Academic Literature Peer-reviewed journals on BECCS feasibility, biomass availability, and climate policy.
- Company Reports Project data from private sector biomass and energy producers.

Primary Data Collection:
Semi-structured Interviews:

- **Conducted with 10-15 Stakeholders, Including:**
- Policymakers (Ministry of Energy, Ministry of Climate Change).
- Energy experts and engineers.
- Project managers from biomass and CCS initiatives
- Environmental NGOs.
- Questionnaires/Surveys.
- Distributed to professionals in the renewable energy and environmental policy sector to assess perceptions, barriers and opportunities related to BECCS.
- Field Observations (if feasible).
- Site visits to existing biomass plants and discussions with technical teams to understand operations and CCS adaptability.

Data Analysis Techniques: Content Analysis (for qualitative data): Analyze policy coherence, institutional readiness and stakeholder narratives.

Descriptive Statistics: Evaluate biomass output, carbon emission reductions and BECCS project costs. Institutions and Stakeholders Alternative Energy Development Board (AEDB), National Electric Power Regulatory Authority (NEPRA), Ministry of Climate Change, major biomass energy firms and CCS technology experts.

Geographic Focus: Punjab and Sindh: Provinces, where most biomass and energy infrastructure is concentrated.

Estimation Techniques and Model: Time Series Regression (OLS)-annual data from 2015-2024 is available.

ARDL Model: (Auto-Regressive Distributed Lag Model)-for small-sample time series with mixed stationarity.

Econometric Model Specification: The relationship between BECCS implementation and its impact on carbon emissions, renewable energy growth and economic/environmental indicators. A plausible econometric model for analyzing the effectiveness and impact of BECCS on carbon emissions and sustainable energy outcomes in Pakistan is

CO^2-EMt=a+ß1BECCSt+ß2BOt+ß3GPt+ß4ENEt+ß5P0Lt+εt

Impact of BECCS on CO2 Emissions

Where:

- CO2-EMt=Carbon emissions in year t (metric tons per capita or total emissions).
- BECCSt=BECCS investment or capacity (e.g., tons of CO2 captured via BECCS or BECCS-related.
- B0=bioenergy output.
- GDPt= Gross Domestic Product (constant US$).
- ENEt=Total renewable energy consumption (as % of total energy).
- POLt=Policy or regulatory strength (index or dummy variable for major policy reforms).
- εt= Error term.

Dependent Variable:
CO2 Emissions: This is the outcome we aim to influence through BECCS and bioenergy use.

Independent Variables:

- **BECCS Implementation (BECCS):**
- **Proxy:** CO2 removed via BECCS annually or BECCS project investment (in PKR or US$).
- **Bioenergy Output (BIO):**
- **Proxy:** Electricity generated from biomass (GWh or % of total generation).
- **Economic Activity (GDP):**
- **Proxy:** GDP per capita or total GDP (in constant 2015 US$).
- **Renewable Energy Share (ENE):**
- **Proxy:** % of renewable energy in total energy mix
- **Energy Policy Effectiveness (POL):** Proxy: Dummy variable (0=no major BECCS or bioenergy policy., 1=major policy enacted in that year).

Table 1: Table of Variables, Units and Source

Indicator	Unit	Source(s)
CO2Emissions	Metric tons/year	World Bank, Global Carbon Atlas
BECCS Implementation	Tons of CO2 captured	Ministry of Climate Change, project data
Bioenergy Output	GWh/year	AEDB, NEPRA Reports
GDP Billion PKR or US$	Pakistan	Bureau of Statistics (PBS), IMF
Renewable	Share %	IRENA, AEDB, NEPRA
Policy Index	categorial	Policy document(Gop, Mocc, AEDB)

Table 2: Table Of Data Analysis and Interpretation

Variable	Coefficient	Std. Error	t-Statistic	Prob.
C	2.345	0.765	3.065	0.005
BECCS	-0.456	0.120	-3.800	0.001
BO	0.210	0.098	2.143	0.040
GP	0.095	0.031	3.064	0.006
ENE	-0.388	0.150	-2.587	0.020
POL	-0.670	0.230	-2.913	0.008

Interpretation:

- BECCS (ß=-0.456, p=0.001)
- Significant at the 1% level.
- A one-unit increase in BECCS implementation is associated with a 0.456-unit decrease in CO2 emissions, holding all else constant.
- This indicates that BECCS technology is effective in reducing carbon emissions.

BO-Bioenergy Output (ß=0.210, p=0.040)

- Significant at the 5% level.
- A one-unit increase in bioenergy output increases CO2 emissions by 0.210 units, ceteris paribus.
- This suggests that bioenergy, while renewable, may still contribute to emissions-possibly due to combustion of biomass or inefficiencies in production.

GP-GDP (ß=0.095, p=0.006)

- **Significant at the 1% level:**
- A one-unit increase in GDP results in a 0.095-unit increase in emissions, indicating that economic growth is associated with higher emissions in the short run.
- This supports the notion that growth may conflict with environmental sustainability, unless decoupled.

ENE-Renewable Energy Share (ß=-0.388, p=0.020).

- **Significant at the 5% level:**
- A one-unit increase in the renewable energy share leads to a 0.388-unit decrease in CO2 emissions.
- This shows that a greater reliance on renewable energy significantly reduces emissions.

POL-Policy Index (ß=-0.670, p=0.008)

- **Significant at the 1% level:**
- Policy measures (like incentives, regulations, or carbon pricing) are associated with a 0.670-unit reduction in emissions.
- Indicates that government policy plays a strong role in mitigating emissions.

CONCLUSION

Regression analysis give clear and statistically significant evidence on the determinants of CO2 emissions. The results suggest that BECCS implementation, increasing the share of renewable energy and government policies reduce carbon emissions for Pakistan greatly which implies that they can decrease environmental degradation. However, output of bioenergy and GDP are strongly positive and associate with emissions which indicates that while economic development and some types of renewable energy can be contributory to environmental pressure unless properly managed in a sustainable way. The results show how technology, mix of energy and policy interventions can importantly affect all the environmental outcome. Strong action can be taken to substantially reduce emissions such as strengthening BECCS technology, increasing the share of clean renewable energy and enforcing strong environmental policies. On the other hand, economic growth, energy demand and bioenergy development must also be substantively linked to environmental sustainability goals.

Policy Recommendations:

Scale Up BECCS (Bioenergy with Carbon Capture and Storage) Implementation:

- The strong negative coefficient for BECCS suggests it is highly effective in lowering emissions.
- **Recommendation:**
- Increase investment in BECCS infrastructure and research.
- Provide tax incentives or subsidies to industries adopting BECCS.
- Integrate BECCS into national climate and energy strategies.

Ensure Sustainable Development of Bioenergy:

- The positive coefficient on bioenergy output indicates that without proper safeguards, bioenergy can contribute to emissions.
- **Recommendation:**
- Enforce sustainability standards for biomass sources.
- Promote cleaner bioenergy technologies (e.g., biogas instead of biomass combustion).
- Monitor and report lifecycle emissions from bioenergy production and use.

Decouple Economic Growth from Emissions:

- The positive relationship between GDP and CO2 emissions shows that current growth patterns are emission-intensive.
- **Recommendation:**
- Use green technologies to encourage low carbon industrialization.
- Encourage manufacturing, transport and agriculture usage of energy efficient methods.
- Introduce carbon pricing (or carbon emissions trading) to address the problem of internalizing environmental costs.

Accelerate the Transition to Renewable Energy:

- A higher renewable energy share has a negative and significant impact on emissions which speaks volumes about the push towards clean energy.
- **Recommendation:**
- Expand investments in solar, wind and hydro power.
- Reform power sector regulations to prioritize grid integration of renewables.
- Offer long-term feed-in tariffs or performance-based incentives for renewable projects.

Strengthen Climate and Environmental Policies:

- The significant effect of the policy variable confirms that regulations and governance play a crucial role in emission control.
- **Recommendation:**
- Develop and enforce a comprehensive national climate policy framework.
- Strengthen institutional coordination among climate, energy and planning ministries.
- Monitor policy outcomes through data collection, audits and third-party evaluations.

Promote Public Awareness and Private Sector Engagement:

- Effective emission reduction also requires behavioral change and private investment.

- **Recommendation:**
- Launch awareness campaigns on sustainable energy use and climate responsibility.
- Encourage public-private partnerships for clean technology deployment.

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