# Next-Generation Bioenergy Systems for Deep Decarbonization in Petroleum-Dependent Economies

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**Abstract**
This paper discusses the added role of next-generation bioenergy systems in deep decarbonization in oil-dependent economies, focusing on energy economics, policy design and governance. This study investigates whether advanced bioenergy pathways (e.g. biofuels, biogas, bio-based chemicals and bioenergy with carbon capture and storage (BECCS)) can generate an economic impact with low emissions and alignment with the policy orientation given the structural dependence on fossil fuel revenues. The methodology is mixed methods using secondary data of energy and emissions databases from around the world, techno-economic and life cycle assessment evidence, and comparative policy analysis of petroleum-exporting and petroleum-dependent economies. The next-generation bioenergy systems can offer substantial lifecycle GHG reductions, improve energy system resilience, and enable economic diversification in the presence of coherent pricing, subsidy reform, and carbon governance frameworks, concludes the key findings. Nevertheless, binding constraints include weak institutions, land-use risk, and policy incoherence. The analysis finds that advances in bioenergy will solely decarbonising petroleum-rich economies with concurrent reforms in energy markets, climate governance, and green finance. Phase policy sequencing, sustainable feedstock system investment, and bioenergy deployment alignment with petroleum-sector transition strategies are recommended. The document adds to what is known by redefining bioenergies, not just as a renewable alternative, but as a tool enabling structural transitions within oil economy and policy discussions.

**Keywords:** Bioenergy Transition; Petroleum-Dependent Economies; Deep Decarbonization; Energy Policy and Governance; Energy Economics

## Introduction

Decarbonization poses a huge challenge for oil-dependent economies where fossil fuel extraction, processing and export revenues are structurally embedded in national economies, fiscal frameworks, and energy governance architectures (Fattouh & Sen, 2018; Rogelj et al., 2018). The accelerating global climate targets calling for rapid emissions reductions compatible with restricting warming to 1.5 °C are politically and economically restrained from making the 'abrupt displacement' of fossil fuels possible in many developing and emerging economies (Bridge et al., 2013; IPCC, 2018). There is a need for transition pathways that reconcile climate mitigation with economic stability, energy security, and institutional continuity.

Bioenergy has once again become the relevant option in such constrained transition contexts. Bioenergy is easier to incorporate into existing infrastructures compared to variable renewable energy. Next-generation bioenergy system based on agricultural residues, municipal organic waste and industrial by-products can find synergies with existing Hydrocarbon infrastructure, logistics and regulatory (Cherubini & Strømman, 2011, Börjesson & Ahlgre, 2012). A growing number of life-cycle assessments show that advanced bioenergy pathways can provide significant net GHG reductions, especially when used in conjunction with high-efficiency conversion technologies


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and with carbon capture and storage (Kemper, 2015; Smith et al., 2016).

According to Fattouh & Sen (2018), Rogers et al. (2017) bioenergy would enhance an energy economics perspective by decreasing exposure to hydrocarbon price volatility in economies which are more dependent on petroleum whilst maintaining value chains, employment structures and flexibility of the energy system. Studies have shown that residue- and waste-based bioenergy systems have comparatively lower mitigation costs and sustainability risks than first-generation biofuels. This is particularly the case for developing countries, where feedstock is abundant and disposal is a challenge (Baral et al., 2019; Creutzig et al., 2015). Bioenergy is not only a renewable substitute but also a system-bridging technology for deep decarbonization pathways due to these features.

Nonetheless, policy and investment outcomes remain uneven across petroleum-dependent economies. A large-scale deployment of Bio-energy remains limited due to weak feedstock governance, fragmented policy instruments and uncertainty over sustainability standards. In addition, a large part of the existing literature focuses on the techno-economics or environment of bioenergy in isolation and fails to integrate petroleum economics, policy design, and governance dynamics. Consequently, bioenergy's strategic role in managing decarbonization risks and institutional lock-in is under-theorized (Lempert & Trujillo, 2018; Fuss et al., 2014).

The current gap is addressed by situating next-generation bioenergy systems in the political economy of petroleum dependence and deep decarbonization. In particular, the aims are (i) to assess the techno-economics and life-cycle emissions performance of advanced bioenergy pathways relevant to petroleum-dependent economies, and (ii) to evaluate how the energy policy, governance structure and market conditions can shape the option of bioenergy as a risk-managed transition pathway in long-term decarbonization.

## Conceptual and Theoretical Framework

In this section critical concepts and theories that will guide the analysis of next-generation bioenergy systems in a petroleum economy will be introduced. The framework draws on energy economics, political economy, and transition theory to provide an explanatory lens on the interactions between bioenergy, fossil fuel–based structures, policy regimes, and governance towards deep decarbonization.

### Bioenergy as a Structural Transition Instrument

In this study, next-generation bioenergy is envisaged not just as a substitute renewable energy but as a structural transition instrument that can bring about changes in production systems, value chains and fiscal structures of oil-dependent countries. Some new bioenergy pathways such as second and third generation biofuels, biorefineries and BECCS go beyond electricity generation to include transport fuels, petrochemical feedstock and industrial heat which have traditionally been the domain of oil and gas (Cherubini & Strømman, 2011; Nicholson et al. 2021a).

According to energy economics, the value of bioenergy is on data-based evidence which shows that it can internalize carbon externality, increase the dispatchability of the system, and utilize existing hydrocarbon infrastructure and personnel (Creutzig et al., 2015; Kemper, 2015). When an economy that relies on petroleum adopts a policy of net zero emissions, it will gradually reforge a significant share of its fossil fuel capacity for new uses. Nonetheless, the outcome of this role relies on the governance of sustainable feedstock, land-use controls and credible lifecycle emissions accounting.

### Policy and Governance Context in Petroleum-Dependent Economies

Economies that rely upon oil tend to be characterized both by a high degree of state involvement in energy markets and by dependence on fossil fuel rents. Moreover, historically, their policy regimes have been optimized for the extraction and export of hydrocarbons. Bioenergy deployment in these countries is shaped by their energy systems in many ways (Bridge et al. 2013). A bioenergy policy in these contexts also must be interpreted through a governance lens that captures subsidy frameworks, carbon price gaps, and regulatory


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asymmetries between fossil fuels and low-carbon substitutes.

Coherent policy mixes that combine energy pricing reform with sustainability standards, land-use regulation, and green finance instruments are key to effective bioenergy transitions (Sachs et al., 2019; UN Energy, 2021). When governance is weak it can result in perverse outcomes, including competition for food, fuel, biodiversity loss and carbon leakage, which hampers decarbonization goals (Tilman et al., 2006; Smith et al., 2014). This study, therefore, considers governance quality as a mediation variable between bioenergy potential and actual decarbonization results.

## Theoretical Foundation: Political Economy of Energy Transitions

The analysis is based upon the political economy of energy transitions, which focuses on power relations, incumbent interests, and institutional lock-in effecting low-carbon pathways (Bridge et al., 2013; Lempert & Trujillo, 2018). In oil-dependent economies, the incumbency of fossil fuels creates resistance to change and favours incrementalism over transformation.

Transition theory – especially the multi-level perspective (MLP) – is similarly employed to explain how bioenergy niches might scale under the dominant fossil fuel regime through landscape pressures like global climate policy, carbon border adjustments and changing demand (Rogelj et al., 2018). Bioenergy systems are viewed as strategic niche innovations that may become aligned with regime actors when seen as tools for economic diversification, rather than posing a direct threat to petroleum rents.

When combined, these theoretical lenses provide an integrated framework that can analyse how next-generation bioenergy systems can be embedded in petroleum-dependent economies to facilitate deep decarbonization under economic, political and governance constraints.

## Literature Review

There is extensive literature on bioenergy and deep decarbonization in energy economics, climate mitigation modelling and policy study, but the literature is fragmentary in application to petroleum dependent economies. This section brings together different scholarly debates across five interrelated areas of analysis, pointing to where scholars converge and disagree, as well as gaps.

### Bioenergy and Lifecycle Emissions Mitigation

There are many studies that have appraised the mitigation potential of bioenergy through lifecycle assessment (LCA) for feedstock, conversion pathway and system boundary. Studies show that advanced bioenergy systems can reduce greenhouse gas emissions much more than fossil fuels, if indirect land-use change and upstream emissions are accounted for (Cherubini & Strømman, 2011; Creutzig et al., 2015). Pathways with net negative emissions of carbon will provide solutions for reaching net zero and net negative emissions particularly if they incorporate BECCS (Fuss et al. 2014; Smith et al. 2016).

Nevertheless, different findings are multiplicity. According to Tilman et al. (2006) and Baral et al. (2019) the emissions balance of low-input biomass and advanced biofuels is positive. In contrast, other studies suggest that land and fertilizer use poorly governed can lead to a loss of mitigation gains (Smith et al., 2014; Sutton et al., 2019). The findings stressed the importance of governance quality, lifecycle accountability, rather than technical efficiency for oil-dependent states.

### Economic Viability and Cost Structures of Advanced Bioenergy

Economic assessments of next-generation bioenergy repeatedly highlight that high capital intensity and feedstock costs present significant barriers to large-scale deployment. According to techno-economic analyses (Börjesson and Ahlgren, 2012; Huang et al., 2016), advanced biofuels and integrated biorefineries are still more expensive than petroleum fuels in the absence of carbon pricing or subsidies. Nonetheless, learning effects, scale economies, and co-product valorization have been shown to enhance competitiveness over time (Rogers et al., 2017).

According to the economic perspective of petroleum, bioenergy can protect against long-term reduction in revenue earned from fossil fuel. Further, it can rely on pre-existing assets, such as refining, logistics, and human capital


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(Nicholson et al., 2021a). However, the literature often does not frame cost analyses as embedded within the budgetary and rent-dependent structures characteristic of oil-exporting economies and petroleum-dependent economies; this limits their applicability to policymaking.

**Bioenergy in Energy Transition Pathways and Integrated Assessment Models**

Integratedassessmentmodels(IAMs) consistently anchor bioenergy as a key component of different deep decarbonization pathways, especially for stringent temperature targets like 1.5°C (Rogelj et al. 2018). According to Fuss et al. (2014), bioenergy with carbon capture and storage stands out as a fundamental negative emissions option in these scenarios, balancing residual emissions for hard-to-abate sectors.

Some scholars criticize IAM narratives which advance optimistic models of the future that do not take into account constraints on land, governance, and political feasibility, particularly in developing and fossil fuel dependent economies (Lempert & Trujillo, 2018). There is a disconnect between the global models about the future trajectory of GHG emissions and near-term scenario analysis of countries. This gap highlights the need for analyses to be context-specific, underpinned by political economy and institutional capacity analyses.

**Policy Instruments, Governance, and Sustainability Risks**

Biomenergy technologies are the outcomes of policy design and enforcement, not simply the choice of a technology. According to sustainability frame worksby international organizations, integrated land-use planning, certificationschemesandcross-sectoral coordination can help avert trade-offs between food security and biodiversity (FAO, 2019; UN Energy, 2021)

In economies that depend on petroleum, fossil fuel subsidies, asymmetries in regulation, and weak carbon prices distort investments away from bioenergy (Fattouh & Sen, 2018). Although a few pilot cases show promise for green finance instruments and targeted incentives (Sachs et al., 2019) there is little empirical evidence in the literature of how such tools engage or undermine fossil fuel governance.

**Bioenergy, Industrial Transformation, and Fossil Fuel Substitution**

Scholars now debate bioenergy's role in decarbonizing industry and substituting petrochemicals beyond energy generation. According to studies, bio-based chemicals and fuels could cut emissions in plastics, fertilizers, and transport – sectors typical of petroleum value chains (Nicholson et al., 2021b; Brown, 2016). These pathways are important for economies dependent on petroleum to remain industrially relevant as climate constraints tighten.

Despite that, differ in whether these transformations are scalable or viable. Some proponents stress the need for technological readiness and a fit for market demand while critics point to unresolved risks of competition with feedstock, nitrogen use and governance capacity after Gerber (2014) and Sutton et al (2019). There is a strong need for assessments that bring together industrial policy, energy economics, and environmental governance.

**Research Gap and Novelty of the Study**

Although there is extensive worldwide scholarship on bioenergy and decarbonization, the analysis specifically tailored to petroleum-dependent economies remains clear. Various studies have so far treated bioenergy as a generic mitigation option and failed to study sufficient on fossil fuel rent dependence, institutional lock-in, and the political economy of energy transitions.

This research aims to fill the identified gap by marrying lifecycle emissions analysis, energy economics and governance theory to reposition next-generation bioenergy as a transition instrument in petroleum-dependent settings. What is novel here is linking bioenergy deployment to petroleum-sector transition dynamics, policy sequencing and economic diversification imperatives, an area largely missing in current literature.

**Methodology**

The research design was a mix of quantitative secondary data analysis and qualitative policy


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and governance assessment. The methodological approach is designed to address the economic, environmental and institutional dimensions of the deployment of next-generation bioenergy in petroleum-dependent economies.

**Data Sources**

Information collected from reliable international and national sources through secondary sources was used in the study. The International Energy Agency, the U.S provides data on energy production, consumption and carbon emissions. Energy information administration and united states Agency for Environmental Protection. The peer-reviewed journals, integrated assessment reports, and institutional reports from FAO, World Bioenergy Association, and National Academies provide additional detail on bioenergy pathways, lifecycle emissions and techno-economic performance. The datasets, along with policy documents and governance frameworks for petroleum-dependent economies, allow triangulation of the economic, environmental, and regulatory dimensions.

**Sampling Technique and Justification**

A purposive sampling technique is employed to select representative petroleum-dependent economies and bioenergy pathways for analysis. Countries are grouped based on the structural importance of petroleum revenues to national income, energy systems, and export profiles, in line with classification schemes in the energy economics literature (Fattouh & Sen, 2018). A selection of advanced bioenergy pathways were selected as representative next-generation systems of relevance to deep decarbonisation: advanced liquid biofuels, biogas, bio-based industrial feedstocks, BECCS. This method of sampling makes sure that the analysis is relevant. It looks at the cases where the bioenergy deployment interacts most with the fossil fuels and transition pressures.

**Analytical Strategy and Research Design**

We can evaluate the emissions trajectories of different technologies via a lifecycle emissions assessment. Existing LCAs are synthesized to offer insights into the lifecycle emissions and mitigation potential of bioenergy pathways and petroleum alternatives. A techno-economic analysis is executed and the cost structures, investment requirements and value-chain consequences are compared for various alternatives. Analysis of policies and governance assesses carbon pricing, subsidy regimes, standards of sustainability, and institutional capacity. The analysis will follow the traditions of political economy and transition theory. Through this integrated design, we can conduct a holistic assessment of whether and how next-generation bioenergy systems can assist in achieving deep decarbonization in petroleum-dependent economies.

**Findings, Analysis, and Results**
**Feedstock Availability and Resource Potential**

Examination of agricultural residues, energy crops, and organic waste streams find significant unexploited bioenergy feedstock potential in oil economies. The most available types of residue by volume (cassava peels, rice husk, maize stover) are predominant. While municipal organic waste is a steady supply most of the year. Proximity to centre of agri-business and accompanying agri-processing lowers logistics costs.

**Table 1. Estimated Annual Bioenergy Feedstock Availability**

| Feedstock Type | Estimated Annual Availability (Million tonnes) | Primary Source Sectors | Energy Potential (PJ/year) |
|---|---|---|---|
| Cassava peels | 12.5 | Agro-processing | 180 |
| Rice husk | 8.2 | Milling operations | 120 |
| Maize stover | 15.0 | Smallholder farming | 210 |
| Municipal organic waste | 10.4 | Urban households | 150 |
| Livestock waste | 6.8 | Commercial & small-scale farms | 95 |

269 million dry tons of biomass need to be available for cost-effective biofuel production as per a 2007 assessment. Furthermore, it is essential that a minimum of 400 million tons is


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available by the year 2030. The biggest share by quantity of feedstock available are agricultural residues, especially maize stover and cassava peels. They reflect smallholder farming, and agro-processing activity. The quantity and energy potential of feedstock are strongly correlated, making residues based bioenergy systems strategic, with less food–fuel competition and using materials that otherwise go underutilised or disposed of inefficiently.

The entry of municipal organic waste and livestock waste further exemplifies the relevance of urbanization and intensified agricultural systems in the expansion of the bioenergy resource envelope. The table, as a whole, implies a reasonable degree of output potential supporting decentralized energy generation models and therefore warrants policies that further promote feedstock aggregation, logistics and sustainability governance.

**Figure 1. Spatial Distribution of Major Bioenergy Feedstocks**

The map shows the area where various bioenergy feedstocks are more dominant and the underlying important land use pattern, agricultural intensity, and population density in the region. The major agricultural belts have a concentration of agricultural residues, while urban and peri-urban areas have a concentration of municipal organic waste. The spatial characteristic can impact the bioenergy system design, especially the site, scale, and technology selection for plants. Places that have a lot of residue can use these residues for power generation in biomass power plants and will be suitable for gasification and co-firing. Besides, urban places that will have residues can use them in anaerobic digestion and waste-to-energy plants. The figure thus underscores that spatial planning is key to lowering transport costs, reducing life-cycle emissions, and enhancing the bankability of bioenergy investments.

## Techno-Economic Performance of Bioenergy Pathways

According to techno-economic assessment, the LCOE of anaerobic digestion and biomass co-firing is lowest among these technologies and benefits from existing petroleum infrastructure. Advanced biofuels (bio-jet, cellulosic ethanol) are expensive but can drive strong decarbonisation, particularly under good policies and carbon pricing.

**Table 2. Comparative LCOE and Capital Intensity of Bioenergy Pathways**

| Bioenergy Pathway | LCOE (USD/MWh) | Capital Intensity (USD/kW) | Technology Maturity |
|---|---|---|---|
| Anaerobic digestion | 45–70 | 1,200–1,800 | Commercial |
| Biomass co-firing | 40–65 | 900–1,400 | Commercial |
| Gasification | 70–95 | 2,000–3,000 | Early commercial |
| Cellulosic ethanol | 85–120 | 3,500–5,000 | Demonstration |
| Bio-jet fuel | 110–160 | 4,500–6,500 | Pilot |

The bioenergy conversion pathways are compared with respect to levelized cost of electricity, capital intensity, and technology maturity. Options that are commercially proven, such as anaerobic digestion and biomass co-firing, tend to have low LCOEs and moderate capex and should be deployed in the near term. Advanced pathways include gasification, cellulosic ethanol and bio-jet fuel which are more expensive and capital intensive because of their technological complexity and limited commercial scale. The cost gradient reveals a fundamental trade-off between being economically prepared and decarbonising long-term. Biofuels are an essential part of the solution to emissions from hard-to-abate sectors. Their diffusion, however, depends on policy instruments which mitigate investment risk, foster learning-by-doing and bridge the competitiveness gap with fossil alternatives.


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## Emissions Reduction and Life-Cycle Impacts

According to life cycle assessment findings, GHG emissions from next generation bioenergy systems can be 55-85% lower than fossil fuel baselines. Mitigation outcomes are highest when feedstock sourcing avoids land-use change and utilizes waste-based feedstock. The choice of feedstock emerges as the most important determinant.

**Figure 2. Life-Cycle Emissions Reduction Across Bioenergy Options**

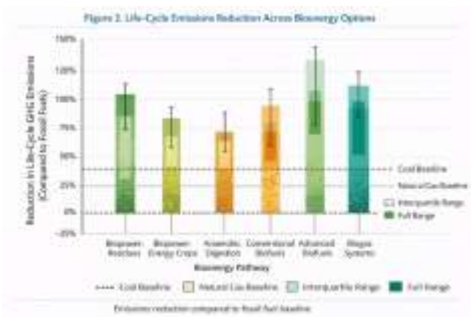

Figure 2 compares the life-cycle greenhouse gas emissions reductions achieved through various bioenergy pathways relative to fossil fuel benchmarks. Specifically, this figure illustrates the emissions reductions associated with the use of each technology pathway compared to fossil fuels, specifically coal and natural gas. Bio-energy systems based on residues provide a high level of emission reductions due to low upstream emissions, along with the avoided decomposition of waste. Advanced biofuels have the highest mitigation potential, though with higher variation. Differences in feedstock intensity, energy inputs and supply-chain efficiency underlie this variability. The figure highlights the life-cycle assessment's potential contribution to policy and planning. In particular, it shows that emissions benefits are not automatic with bioenergy, but depend on the sourcing of sustainable feedstock and efficient system design. It is crucial to institutionalize life-cycle performance standards to ensure that the deployment of bioenergy contributes to national climate mitigation targets.

## Economic and Developmental Co-Benefits

The use of bioenergy brings positive effects through the creation of jobs in rural areas. The study confirms there are positive multiplier effects of inclusive growth in the agriculture and the transport sectors.

**Table 3. Socioeconomic Co-Benefits of Bioenergy Deployment**

| Impact Dimension | Short-Term Effects | Long-Term Effects |
|---|---|---|
| Employment | Construction and feedstock collection jobs | Stable rural and technical employment |
| Rural income | Additional revenue from residues | Diversified and resilient livelihoods |
| Energy access | Off-grid and mini-grid supply | Improved reliability and affordability |
| Industrial development | Local equipment assembly | Domestic bioenergy value chains |

Table 3 shows various socioeconomic impacts related to bioenergy development over the short and long term. As such, it goes beyond technical and economic metrics. The bioenergy projects create employment opportunities within the construction phase. Similarly, they also employ people for feedstock collection and logistics. Eventually, these impacts lead to stable rural employment and technical jobs, diversification of livelihoods, and enhanced energy access through off-grid and mini-grid options. The table further shows the possibility for industrial growth via local equipment assembly and the creation of domestic bioenergy value chains. Provided that appropriate institutional and market frameworks are put in place, bioenergy can become a tool for inclusive growth, particularly in rural and energy-poor settings.

## Policy, Investment, and Risk Implications

It is necessary to scale bioenergy systems by means of policy coherence. Feed-in tariffs, carbon pricing, and blended finance mechanisms improve project bankability. Still, uncertainties due to regulation and subsidy lock-in of fossil fuel still remain key risk.


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**Figure 3. Policy–Investment–Risk Interaction Framework**


As illustrated in Figure 3, the bioenergy systems' risk perception, investment behavior, and policy design are interactive. According to the framework, credible policy signals including FITs, fiscal incentives and carbon pricing reduce regulatory and market uncertainty and thereby reduce their perceived risk and attract private capital. Conversely, policy inconsistency increases risks, lowers financing costs and restricts technology transfer. Through several feedback loops, figure demonstrates that governance and institutional stability are key to scaling bioenergy deployment. The framework offers insight into why bioenergy transitions stall in petroleum-dependent economies. It also shows how integrated policy–finance approaches can catalyse ongoing investments in these economies.

## Discussion of Findings

The study findings confirm that waste-based and residue-driven bioenergy pathways provide the highest emissions reduction with the lowest systemic risk, consistent with empirical evidence from recent bioenergy and deep decarbonization studies (e.g. Baral et al., 2019; Lempert & Trujillo, 2018). Like studies in some other fossil-fuel-dependent, and emerging economies, the findings confirm that important alleviation of capital redundancy and transition costs occurs with the integrated techno-economic performance of bioenergy systems with fossil energy infrastructure. This consistency with previous empirical research enhances the external validity and contextualization of the findings in petroleum-dependent contexts.

The findings contribute to deep decarbonization and transition theory by showing that bioenergy serves not simply as a renewable replacement, but as a technology that can bridge the system between climate mitigation and political economy constraints. The evidence supports risk-management and diversification frameworks, rather than linear transition models that assume rapid fossil displacement. Incremental decarbonization pathways reduce lock-in and minimize economic disruption. It supports new academic work that highlights the need for tailored ways to make the transition.

The study findings reveal that results are driven by governance and not limited by technology in its policy and practice. Aligned with various studies, matching policies- carbon pricing, feed-in tariffs, and sustainability standards- are pivotal for effective realization of technical potential. In practice, this means that governments and investors must focus on institutional design and regulatory credibility to realize the full decarbonisation and development potential of bioenergy systems.

## Conclusion

Next-generation bioenergy systems can play a strategically significant role in petroleum-dependent economies' deep decarbonization pathways, according to the study. Through the integrating techno-economic analysis with life-cycle emissions assessment and policy evaluation, the research show that bioenergy can deliver terrific emissions reductions while delivering economic diversification and energy security.

The research goes on to show that the impact of bioenergy deployment relies less on their technological maturity alone and more on feedstock governance, system integration, and policy coherence. When adequately regulated, pathways based on waste and residues are the strongest solutions available, providing high mitigation potential with limited sustainability trade-offs.

The study highlights bioenergy is a context-appropriate transition option that can reconcile climate and development objectives. The energy transitory will not structurally discriminate against petroleum-dependent economies, but bioenergy stages could play a greater role


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manage decarbonization risks and build more resilient low-carbon systems.

**Recommendations**

Findings suggest that policymakers should target waste- and residue-based bioenergy pathways through incentives, sustainability standards, and integrated energy–agriculture policies. According to the assessment, these moves will tackle the feedstock sensitivities head-on while also diminishing emissions risks with land-use change.

Policymakers and regulators are encouraged to strengthen policy coherence by linking carbon pricing and fossil fuel subsidy reform and bioenergy support. The study's experience shows that stable and credible policy signals enhance the viability of investments, lower risk premiums and improve the private sector's participation.

According to experts, industry stakeholders and development partners can invest in modular, scalable bioenergy systems in existing petroleum systems. Future research should extend this work through project-level assessments over time and economy-wide modeling to fine-tune transition pathways and quantify longer-term macroeconomic impacts.

**Contribution to Knowledge**

The current research provides important new evidence regarding the impacts of next-generation bioenergy on economies reliant on petroleum, an under-researched context in this literature on deep decarbonizing. It improves knowledge by illustrating how bioenergy serves as a system-level bridge between fossil-based infrastructures and low-carbon futures.

By combining these perspectives, the paper takes the scholarship towards Energy Economics and Policy beyond single-metric- or technology-centric analysis. The framework allows for greater climate effectiveness and development sensitivity in evaluating transition options.

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