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# A Nepal Perspective on Closing the Carbon Cycle Pathways to De-fossilize Difficult-to-Electrify Sectors in a Hydropower-Dominated Economy

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***Abstract***

Urgent decarbonization of energy systems, industrial processes and transportation is necessary to mitigate GHG emissions. Though Nepal generates more than 95% of electricity from hydropower, still there are difficult-to-electrify sectors like transportation, fertilizer production, cement and brick industries, which are fossil fuels dominated. This dependency causes increase in fuel imports, emissions, and climate risks. This paper studies how Nepal can move forward towards a circular carbon economy by adopting the principle of closing the carbon cycle, originally developed in the US context, to Nepal's hydropower-dominated and resource-constrained economy. Using a qualitative and systems-oriented approach based on secondary literature, policy documents, and sectoral reports, the study identifies key scientific and technological opportunities, including green hydrogen and ammonia production from surplus hydropower, carbon capture and utilization in cement and brick industries, and waste-to-energy systems for urban resilience. Based on this adaptation, a Nepal-specific conceptual framework is proposed to connect energy, industry, agriculture, and waste systems so that carbon can be reused across multiple applications before final disposal. The paper also highlights policy implications, investment considerations, and a phased research and innovation roadmap emphasizing enabling regulations, financial incentives, pilot projects, and inclusive governance. The study concludes that Nepal can position itself as a model for decentralized, low-carbon development by strategically aligning renewable electricity, carbon reuse pathways, and sector-specific transition policies.

***Keywords****—Decarbonization, Difficult-to-electrify, Resilience, Framework, Implication, Innovation, Decentralized*

## 1. INTRODUCTION

Climate change has become global issue which needs to be addressed with the urgent priority through the rapid decarbonization of energy systems, industrial processes, and transportation networks. Renewable Energy (RE) based electrification is now considered as one of the most effective ways to mitigate this problem by reducing Green House Gas (GHG) emissions. But still there are many sectors which are too difficult to electrify because of technical, economical and infrastructural constraints. These so-called difficult-to-electrify sectors like long-haul transport, aviation, cement and steel producing industries, and large-scale chemical processing plants depend on carbon as basic input. Thus, there arises urgent need to "close the carbon cycle" such that carbon is reused, recycled or replaced with non-fossil fuel alternatives thus enabling a sustainable, circular carbon economy.

Although Nepal remains the country whose emission is low compared globally, still faces unique challenges and opportunities regarding this transition. Nepal has set an ambitious target to achieve net-zero emissions by 2045. Nepal possess one of the major advantages with regards to industrialized economies as its electricity sector is dominated by RE, with more than 95% of electricity generation through hydropower. This will strongly help Nepal to electrify light electric vehicles, household appliances, and industries with modest energy demand. Despite that significant part of Nepal's economy still depends upon fossil fuels. Petroleum imports for road transport, aviation, diesel generators, and industrial boilers covers the major share of the national trade deficit. Liquified Petroleum Gas (LPG) is still the primary source of cooking while cement industries and brick kilns heavily rely on coal and furnace oil. In conclusion, these sectors can be considered as difficult-to-electrify sectors in Nepal.

The difficulty in electrifying these sectors is not only due to technical barriers but also due to country's geographical and economical aspects. Since Nepal being a landlocked and mountainous country, it faces high transportation costs, fragmented supply chains and scattered industrial hubs. Rural areas mostly still depend upon traditional biomass for cooking and heating thus creating environmental as well as health problems. On the other hand, urban areas face major problems with rapidly growing unmanaged solid waste, majority of which produces methane in landfills. Also due to rapid increase in demand of construction materials like cement, steel and bricks due to urbanization and infrastructure development cause increase in fossil fuel consumption.

Because of these realities, there is a strong need of strategic plan that goes beyond electrification. Thus, the concept of de-fossilization; i.e. removing fossil fuels while still keeping carbon in play, can offer a strong pathway. By making strong use of its abundant hydropower, Nepal can explore the options of producing green hydrogen and ammonia, thus enabling low carbon fuels and domestic fertilizer production. Also, biomass residues, food waste, plastics and biogas can be converted into useful feedstocks so that carbon atoms can be used multiple times before disposal. Circular economy can be further enhanced by capturing and utilizing carbon emissions from cement and industrial plants.

This research explores how Nepal can design its own roadmap for closing the carbon cycle through international exposures and identifying solutions best suited to local conditions. In this paper, identification of key scientific opportunities, evaluation of alternatives to carbon-based fuels and assessment of pathways to reuse non-fossil carbon are the major points discussed. Ultimately, the main objective is to outline how Nepal can de-fossilize its difficult-to-electrify sectors to meet its net zero by 2045 target, improving energy security and fostering socio-economic resilience.

## 2. LITERATURE REVIEW

Efforts are being made globally to decarbonize energy systems with emphasis on electrification through renewable resources, with focus on solar, wind and hydropower particularly. However, the studies done by Intergovernmental Panel on Climate Change (IPCC), International Energy Agency (IEA), and national energy transition studies have identified long haul transport, cement, aviation, and high temperature industrial processes as difficult-to-electrify sectors. [1] [2]These so called difficult-to-electrify sectors present persistent challenges to net-zero goals. [3]Beyond direct electrification, these sectors require alternative energy carriers or carbon reuse technologies and strategies.

The role of green hydrogen, ammonia and CCU in closing the carbon cycle has been significantly highlighted by the recent studies from the US Department of Energy and European Commission.[4] [5] These technologies allow carbon atoms to be used across multiple applications before final disposal thereby reducing dependency on fossil fuels while maintaining the industrial functionality. [6] Ellen MacArthur Foundation proposed circular carbon economy frameworks, which was adopted in China's biorefinery models, emphasize modular, decentralized systems that valorize waste and biomass. [7] [8] India's National Hydrogen Mission and pilot CCU projects in cement industries are providing valuable insights into scaling low-carbon technologies within the resource and infrastructure constraints even for other South Asian countries. [9] [10] Nepal's own energy transition studies, reports from WECS, AEPC and ICIMOD highlights the nation's hydropower dominance in electricity sector and the urgency to address dependency on fossil fuels for transport, cooking and industrial sectors. [11] [12] [13]

Despite these advancements being made globally and regionally, there is still limited research carried out regarding Nepal specific carbon circularity. Most of the studies are focused on electrification and biogas deployment, with only few addressing integrated carbon reuse pathways. This gap offers both a challenge and opportunity so as to adapt proven international models to Nepal's decentralized geography, biomass availability and socio-economic conditions.

This research combines global research on carbon cycle while especially focusing on Nepal's energy, industrial and policy landscape. Additionally, it proposes a locally adapted framework for de-fossilizing difficult-to-electrify sectors through strategic reuse, recycling and replacement of fossil fuels.

## 3. METHODOLOGY

This research employs a combination of qualitative and analytical approach to explore how the principle of closing the carbon cycle can be adopted specifically for Nepal's hydropower dominated energy sector. The methodology can be best described by the following steps shown in the flowchart:

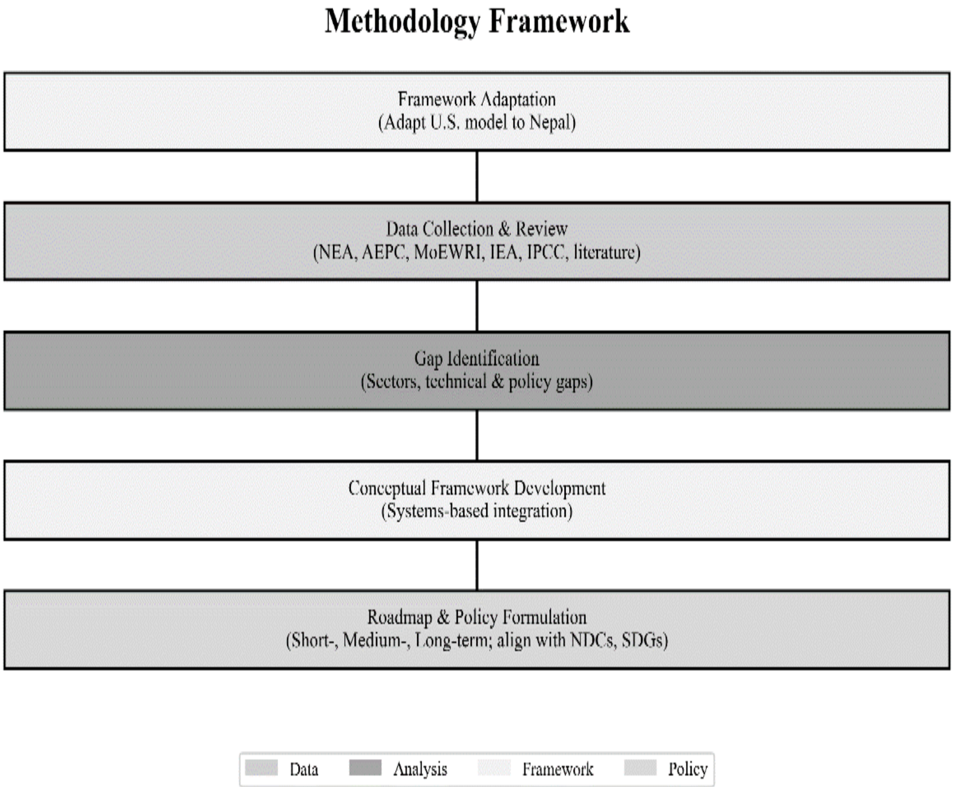


**Figure 1**: Methodology Framework

A. **Framework Adaptation:**

The baseline conceptual model is derived from the US perspective on closing the carbon cycle, specially focusing on carbon reuse, carbon recycling, and carbon substitution for difficult to electrify sectors. These core principles were used as conceptual blocks rather than directly adopting as policy prescriptions. To adapt this framework into Nepal, elements like hydropower dominance in electricity generation, dependency on imported fossil fuels, decentralized and mountainous geography, availability of biomass and municipal waste, industrial sectors dominated by cement and bricks, etc. were analyzed. On the basis of this framework adaptation, identification of most relevant carbon cycle pathways and modifications needed due to scale, infrastructure, investment capacity, and market readiness constraints were identified.

B. **Data Collection and Review:**

Secondary data were collected from reports of NEA, AEPC, Ministry of Energy, Water Resources and Irrigation (MoEWRI) as well as international database like IEA, IRENA, IPCC, etc. The review of peer reviewed literature on hydrogen, biofuels, waste-to-energy and carbon capture was done to identify technology options viable to Nepal; with two main focus: first identifying internationally recognized technical pathways for de-fossilizing difficult-to-electrify sectors, and secondly screening the pathways for their relevance to Nepal's energy, industrial, agricultural, and waste management context.

### C. Gap Identification:

A qualitative gap identification approach was used to make comparative analysis between Nepal's current energy mix and projected demand was conducted to identify difficult-to-electrify sectors. The identification and mapping of institutional, technical and policy gaps were done on the basis of existing national strategies and climate commitments. The process involved three layers of assessment: first, difficult to electrify sectors were identified by reviewing the sectors that rely heavily on fossil fuels despite the country's renewable advantage. Secondly, a qualitative comparison for each sector was made on the basis of fossil fuel dependence, availability of renewable or carbon-circular alternatives, infrastructure readiness, institutional and regulatory support. Finally, the gaps were categorized based on technological gaps, institutional and policy gaps, and knowledge and capacity gaps.

### D. Conceptual Framework Development:

Based on the adapted framework and the identified gaps, an integrated conceptual framework linking hydropower, hydrogen, ammonia, biomass, and waste valorization with carbon circular economy. The framework was developed focusing on energy, industry, agriculture and urban waste systems. Pathways were included in the framework only if they satisfied one of the criteria like reduction of fossil fuel dependency in a difficult-to-electrify sectors, possibility of reuse or recirculation of carbon before final disposal, compatible with Nepal's decentralized geography and renewable resources-based areas and ability to introduce through modular ot pilot-scale development.

### E. Roadmap Formulation:

A phased research and innovation roadmap were developed by synthesizing globally best practices with Nepal specific constraints. Policy implications were derived by aligning proposed pathways with Nepal's net-zero by 2045 target, NDC commitments and SDG goals.

## 4. RESULTS AND DISCUSSION

Nepal's unique position in advancing a circular carbon economy is the major highlight and findings of this study. With more than 95% hydropower dominated electricity sector, Nepal possesses a renewable foundation that most of the countries in the world do not have. However, fossil fuel still remains dominant in difficult-to-electrify sectors and these sectors carry large share of fossil fuel imports, which in turn increase Nepal's trade deficit and expose the economy to external shocks.

## A. Fundamental Science Opportunities for Nepal

In order to achieve Nepal's net zero by 2045 target, it is necessary to have rapid electrification as well as strategic plan for sectors that are difficult to electrify. The US perspective highlights that discovery and deployment of transformative technologies is too slow to achieve urgent climate goals. But in case of Nepal, the challenge is different. Though the country doesn't have large scale Research and Development (R&D) facilities for advanced energy materials or catalytic process but Nepal do have unique opportunities to make direct advancement towards proven international tools and technologies while giving priorities to context specific innovations at smaller scales. Some of the major promising scientific opportunities are briefly explained below:

### a. Green Hydrogen and Ammonia from Hydropower:

Nepal's electricity sector is hydropower dominated and the generation is often very high during monsoon periods. This seasonal high generation from hydropower can be used as a foundation for green hydrogen production through water electrolysis. The studies conducted by Water and Energy Commission Secretariat (WECS) and ICIMOD recommend that a small-scale hydrogen hub near large hydropower stations like Upper Tamakoshi (456 MW) or Arun III (900 MW) under construction can be developed as pilot projects. The hydrogen thus obtained can be used to replace LPG in cooking, to support fuel cells for heavy duty trucks or to serve as feedstock for green ammonia production, thereby reducing dependency on imported fossil fertilizers. Nepal is currently facing a heavy financial burden by importing over 700000 tons of chemical fertilizers annually. This burden can be significantly reduced through domestic production of green ammonia while simultaneously reducing emissions too.

### b. Carbon Capture and Utilization (CCU) for Cement and Bricks:

Nepal's cement industry is the industrial sector that contributes largest industrial emission, contributing 3.45 million metric tons of $CO_2$ in 2019. On contrary to diffuse emissions made from transportation sector, these emissions are heavily concentrated in relatively fewer plants, thus making them suitable for capture and reuse. Larger cement industries like Hetauda Cement and Udayapur Cement do operate with large kilns where pilot projects of $CO_2$ capture can be initiated. In case of brick kilns, significant reductions in emissions can be achieved by converting them into Vertical Shaft Brick Kilns (VSBKs) or Hybrid Hoffman Kilns (HHKs). Combining these modern kilns with CCU technologies could further reduce their carbon emissions.

**c. Biomass Valorization and Distributed Biorefineries:**

One of the major untapped carbon sources in Nepal is agricultural residues like rice husk, sugarcane bagasse, and maize stalks are often burned in open fields, releasing black carbon and methane. Nearly 3.6 million tons of sugarcane is produced in Nepal annually. If fully harnessed 30-40 MW of electricity could be produced from sugarcane bagasse. Currently, the country has been able to utilize only a fraction of this potential. Nepal already has made its marks on biomass to energy conversion with over 400000 household biogas plants installed. By scaling this model to community level biorefineries it is possible to produce transport fuels, fertilizers and power simultaneously.

**d. Waste-to-Energy and Circular Urban Systems:**

Over 1200 tons of municipal solid waste (MSW) is generated inside Kathmandu only in daily basis; with more than half of the MSW being organic. Landfills like Sisdol and Bancharedanda emit methane which is a potent GHG. Though several pilot projects regarding waste-to-energy have been initiated, most of them failed due to poor segregation and mixed waste streams. One of the cases, Teku Waste-to-Energy Pilot Project (2017) could not be scaled due to inconsistency in feedstock quality. There is lack of provision of recycling of plastics with less than 10% of plastics in Nepal being recycled and remaining portion being thrown into landfill and river streams.

**e. Integration of Modular and Low-Cost Technologies:**

In Nepal mega-scale industrial facilities like those in US are not feasible due to geographical constraints. But still Nepal can utilize the opportunity through small, modular units that can be deployed locally. Like trying containerized biogas digesters for hotels or hospitals in Kathmandu, micro-gasifiers for rice mills in Terai, etc.

**f. Knowledge Gaps and Capacity Building:**

The most critical challenge lies in the limited scientific and technical workforce in advanced chemical engineering, catalysis and process integration. Though Nepal's universities like TU, KU, PU, etc. and research organization likes NAST, AEPC, etc. are conducting research works on RE but advanced carbon utilization R&D is still in initial phase. By learning from India's hydrogen and carbon capture initiatives and China's biorefinery technologies, Nepal can make quick progress in this sector. Nepal could get funding and technical support through international collaborations with ICIMOD, IRENA, UNDP, etc.

## B. Conceptual Framework: Closing the Carbon Cycle

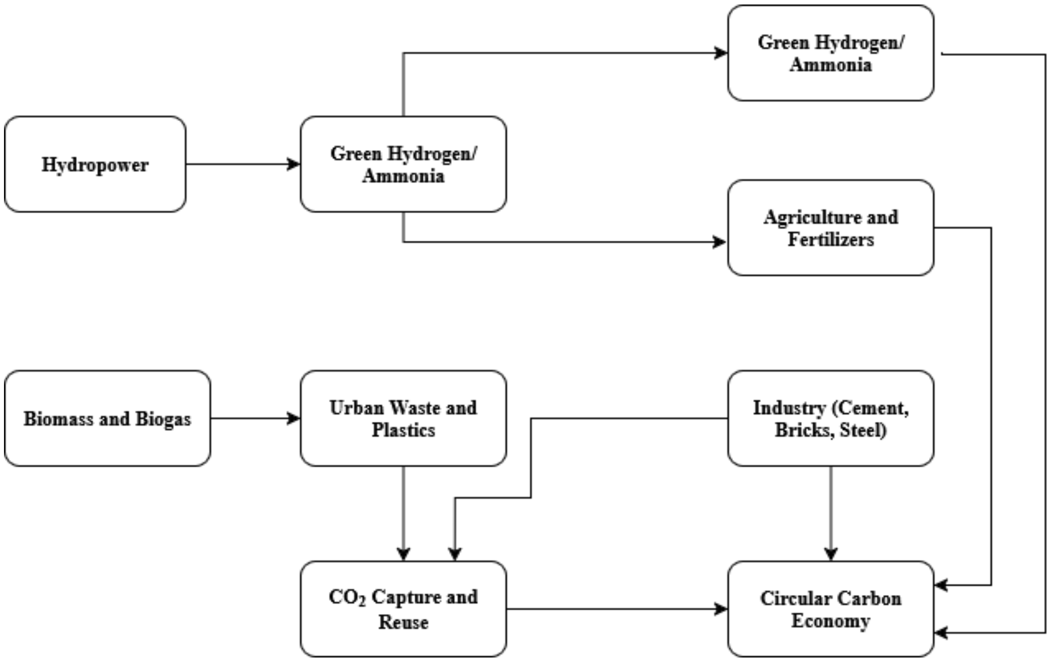


**Figure 2**: Conceptual Framework: Closing the Carbon Cycle

The conceptual framework as shown in Figure 2 shows how Nepal can make progress towards a circular carbon economy by making strategic linkage between its abundant renewable sources difficult-to-electrify sectors. Nepal's hydropower sector is the core source of electricity that provides the basis for producing green hydrogen and ammonia. These fuels can be directly used to support difficult-to-electrify sectors like long haul transportation and fertilizer production for agriculture. On the other hand, dependency on fossil fuels can be reduced along with the advantage of mitigating environmental burdens though biomass residues, biogas and urban waste streams, including plastics. Similarly, the cement, brick and steel industries which are major point sources of $CO_2$, can be integrated into the framework through CCU, with $CO_2$ reused for synthetic fuels or chemical production. Together, these interconnected pathways show how Nepal can "keep carbon in play" while de-fossilizing its economy so that carbon atoms are recycled across multiple uses before finally disposing. The framework therefore prioritizes a decentralized, resource efficient approach which leverages Nepal's renewable strengths and also addresses the unique challenges of its industrial, agricultural and urban systems.

## C. Alternatives to Carbon-Based Fuels in Nepal

Though Nepal's renewable hydropower-based electrification can address a significant portion of demand in households, services and urban mobility, there are still certain sectors present in the economy which are difficult to electrify. These difficult-to-electrify sectors already mentioned above, require energy carriers that go beyond electrons. In this regard, alternative fuels based on renewable sources provide promising alternatives for de-fossilizing country's economy.

| Alternative | Potential Applications in Nepal | Advantages | Challenges | Nepal-Specific Relevance |
|---|---|---|---|---|
| **Hydrogen ($H_2$)** | Long haul transportation, fertilizers feedstocks, steelmaking, etc. | Zero-carbon production, versatile applications, leverages hydropower surplus, etc. | Storage challenges, safety concerns, high CAPEX for electrolyzer, etc. | Applicable to initiate pilot projects near large hydropower plants |
| **Ammonia ($NH_3$)** | Production of fertilizers substituting urea, hydrogen carrier, potential engine fuel, etc. | Dual role: both fuel and fertilizers | Toxicity, need of infrastructure development, energy-intensive synthesis, etc. | High potential to reduce large fertilizers import every year thus supporting agriculture and trade balance. |
| **Biofuels** | Biogas for cooking, biodiesel for diesel blending, ethanol for petrol blending, etc. | Use of domestic residues, reduction of wastes and rural pollution, etc. | Fragmented supply chains | Rural based application, bagasse and rice husk can be used to support local biorefineries, etc. |
| **Waste-Derived Fuels (MSW, plastics)** | Derived fuel option for cement kilns, biogas production from food waste, pyrolysis oils from plastics, etc. | Reduction in landfill and pollution, creation of circular economy, etc. | Failure of pilot projects, mixed waste streams, weak segregation, etc. | Urban friendly if segregation is improved |
| **Electricity (Direct Use)** | e-cooking, light-duty EVs, industrial low temperature heat, etc. | RE based with high efficiency, reduced costs, etc. | Grid reliability, lack of EV charging infrastructure, etc. | Highly relevant as large hydropower shares in the grid, best suited for households and urban transport applications, etc. |

## D. Policy Implications for Nepal's Carbon-Cycle Transition

Nepal's target to reach carbon-neutral future especially in difficult-to-electrify sectors is only achievable with strategic realignment of energy, industrial and environmental policies. Carbon-free fuels and carbon-reuse technologies should only be deployed with the strong backing by enabling regulations, targeted incentives, and inclusive governance frameworks.

**a. Integration of carbon alternatives into national energy strategy**

Nepal's current energy policy like the National Renewable Energy Framework and the Long-Term Strategy for Net Zero Emissions gives emphasis to electrification and hydropower expansion. However, in order to address difficult-to-electrify sectors in the effective way, the government must:

(i) Make green hydrogen and ammonia as strategic energy carriers within national planning documents.

(ii) Develop technical standards and safety codes for decentralized production, storage and proper use of these fuels.

(iii) Create pilot projects with the backing of AEPC and other similar organizations to test the modular systems in rural as well as urban scenarios.

**b. Provision of Incentives to Distributed Carbon-Reuse Technologies**

With the use of country's abundant agricultural and forest residues, biochar, pyrolysis and syngas-based fuels offer viable pathways so as to keep carbon in play. In order to scale these technologies, the policy should:

(i) Introduce feed-in tariffs or credit mechanism for the production of biochar, pyrolysis oils and syngas-based fuels and utilize the revenue in soil enhancement.

(ii) Make plan for capital subsidies or special loans for community-based pyrolysis and gasification units.

(iii) Mandatorily integrate carbon reuse systems in brick kilns and agro-processing zones though updated license norms.

**c. Alignment of Carbon Cycle with Climate Finance**

Nepal can enhance its access to international climate finance through mechanisms like Green Climate Fund (GCF), Clean Development Mechanism (CDM), and other bilateral aid in order to support carbon-cycle technologies and innovations. Policy actions should:

(i) Develop bankable project pipelines which bundle modular carbon cycle systems along with measurable mitigation outcomes.

(ii) Establish a national carbon registry so as to track life cycle emission reductions and monetize additional benefits like air quality, soil health, etc.

(iii) Promote Public-Private-Partnerships (PPP) to co-develop technologies and innovations in collaboration with local universities or communities.

**d. Ensuring Equity and Inclusion in Technology Deployment**

Carbon cycle solutions must be designed and governed in such a way that marginalized communities, especially in mountain and hilly regions are benefitted. Policy frameworks should:

(i) Give preference to deployment in areas with limited grid access and huge biomass availability.

(ii) Include participation of women's cooperatives, community forest user groups, and local governments in planning and ownership.

(iii) Ensure social safeguards and participatory monitoring in all funded projects.

**e. Building Institutional Capacity and Regulatory Readiness**

Nepal must strengthen its institutional capacity across ministries and technical bodies in order to ensure effective implementation. The policy guidelines should:

(i) Conduct hands-on training for regulators, engineers, and technicians in carbon technologies and safety protocols.

(ii) Update Environmental Impact Assessment (EIA) guidelines to include carbon reuse and alternative fuels.

(iii) Establish inter-ministerial coordination platforms linking energy, environment, agriculture and industry.

**f. Investment Requirements, Cost Barriers, and Financial Risks**

While the proposed technologies can reduce fossil-fuel imports and strengthen energy security, their implementation in Nepal is constrained by major financial challenges. Green hydrogen, ammonia, and CCU pathways require high upfront investment in equipment, storage, process integration, and safety systems, while decentralized bioenergy and waste-to-energy systems, although smaller in scale, still require capital support, feedstock management, and technical maintenance. A major barrier is that many low-carbon alternatives remain more capital-intensive than conventional fossil-fuel-based practices, particularly in the early stages of deployment. Additional constraints include dependence on imported equipment, foreign exchange exposure, weak domestic supply chains, limited concessional finance, and low market maturity.

The main financial risks include technology performance uncertainty, long payback periods, regulatory and policy instability, uncertain off-take demand, and inconsistent biomass or waste feedstock quality. Therefore, Nepal should adopt a phased financing strategy. Capital-intensive technologies should begin with pilot and demonstration projects supported by concessional finance, climate funds, and public-private partnerships, while more modular and decentralized options can be prioritized where local resource availability improves feasibility. Policy tools such as soft loans, capital subsidies, viability gap funding, and project preparation support will be essential to reduce risk and improve bankability.

**E. Research and Innovation Roadmap for Nepal**

Nepal's intention to attain a de-fossilized economy relies upon not only on policy direction but also on targeted research, innovation and capacity building. With the limitations of large-scale laboratory facilities and industrial R&D hubs, but still Nepal can leverage its unique context by prioritizing on decentralized, low cost and modular solutions. Therefore, it is necessary to have a phased research and innovation roadmap to guide universities, industries and policymakers towards coordinated action.

| Timeframe | Focus Areas | Key Actions / Research Needs | Expected Outcomes |
|---|---|---|---|
| **Short-Term (0–5 years)** | Demonstration & Adaptation | Pilot hydrogen hubs near hydropower plants<br>Feasibility of small-scale ammonia synthesis<br>Smart grids, EV charging corridors, induction cooking<br>Community-scale biorefineries (rice husk, bagasse)<br>Pilot waste-to-energy (AD, pyrolysis) - University-industry pilot labs ($H_2$, biomass, CCU)<br>Graduate programs on carbon circularity | Demonstrated pilots, improved grid integration, initial capacity building, local innovation ecosystem established |
| **Medium-Term (5–10 years)** | Scaling Up & Integration | Industrial-scale hydrogen & ammonia<br>Modular CCU in cement & bricks<br>Ethanol blending (5–10%), biodiesel expansion<br>RDF in cement kilns, mandatory waste segregations<br>AI/digital twins for optimization<br>Regional research collaboration (ICIMOD, India, China) | Industrial adoption of alternatives, reduced imports (fertilizer, fuels), cleaner urban systems, regional leadership emerging |

| | | | |
|---|---|---|---|
| **Long-Term (10–20 years)** | Leadership & Circular Economy |  Cross-border hydrogen/ammonia trade<br> Commercial CCU-to-chemicals (methanol, fuels)<br> Synthetic aviation fuels<br> Zero-landfill urban systems<br> Nepal as model for decentralized circular carbon solutions<br> International research collaborations & human capital development | Full integration of circular carbon economy, export of decentralized solutions, energy independence, contribution to global decarbonization |

## 5. CONCLUSION

Nepal is at a crucial point regarding its energy and development trajectory. Being hydropower dominated energy sector, the country has a unique opportunity as well as challenge to accelerate the global shifting from fossil fuels towards carbon circularity to develop economies. Though the most immediate and cost-effective pathway is offered by electrification through e-cooking, electric mobility, and smart grid expansions, but the difficult-to-electrify sectors like heavy transport, fertilizer production, high temperature industrial process still require alternative solutions.

This study has outlined the pathways to complement direct electrification in Nepal's context through green hydrogen, ammonia, biofuels and waste-to-energy mechanism. Altogether these alternatives help to "keep carbon in play" by reusing carbon atoms across fuels, fertilizers, and industrial process before their final disposal. The conceptual framework presented here illustrates the ways to integrate energy, industry, agriculture and waste systems into a circular economy so as to minimize reliance on fossil imports while enhancing energy security and resilience.

To make this vison into a reality, technical enhancements alone will not enough. It will require enabling policy frameworks ranging from grid modernization and electrification incentives to green hydrogen strategies, biofuel mandates and waste segregation regulations to create market readiness. The research and innovation roadmap prioritize the phased action: short term pilot projects and capacity building, medium term scaling and industrial integration and long-term technological leadership through cross border trade, advanced CCU and zero landfill systems.

The country's abundant renewable resources should be strategically aligned with scientific innovation and policy support to leapfrog into a sustainable energy future. By doing this, it not only advances its own development priorities and climate commitments but also positions itself as a global example illustrating how a low-income, resource-constrained country can design decentralized, affordable and inclusive pathways towards de-fossilization.

## 6. SUGGESTION AND RECOMMENDATION

This study presents a comprehensive conceptual framework, comparative analysis, policy implications and a research roadmap but still there are several areas that still require further investigation. At first, it is necessary to conduct detailed techno-economic assessments of green hydrogen, ammonia, biofuels and waste-to-energy pathways in order to evaluate their cost competitiveness and scalability under Nepal's specific conditions. Secondly, life cycle environmental assessments should be carried out to quantify the net GHG reductions and co-benefits of alternative fuel pathways. Third, it is necessary to carefully monitor pilot and demonstration projects to generate data which can be useful information for both policy and industrial investments.

In future research, focus should also be given to regional collaboration opportunities, particularly in cross-border electricity trade, hydrogen and ammonia exchange and shared innovations platforms with India and China. It is equally important to integrate socioeconomic dimensions like rural employment, gender equity, and energy access into de-fossilization strategy to make sure that inclusivity and justice are served in Nepal's energy transition. Finally, continued engagement between academia, industry and government will be very important in the operations of the circular economy envisioned in this study.

By addressing these future recommendations, it will be possible for Nepal to transform its scientific and policy ambitions into actionable pathways that demonstrate to the world that how a developing country with abundant renewable energy resources can be an exemplary leader in closing the carbon cycle.

## 7. LIMITATION OF THE STUDY

Even though this study presents a comprehensive conceptual framework for adapting circular carbon economy principles to Nepal, there remain several limitations that need to be acknowledged. Firstly, the analysis primarily is carried out based upon the secondary data that are available in national reports, international literature and policy documents. The lack of high resolution, real time energy system data from Nepal limits the precision of quantitative assessments, which may affect the accuracy of comparative cost and feasibility estimations.

Secondly, although the study identifies hydrogen, ammonia, biofuels and waste to energy as potential alternatives, but a detailed techno-economic analysis (TEA) or life-cycle assessment (LCA) is not conducted for each pathway. Due to this, the environmental, financial and operational trade-offs are conceptually outlined rather than empirically validated. Since the proposed research and innovation roadmap is based on extrapolations from global experiences, it is intended as a guiding framework rather than a perspective plan. So, to make it perspective plan, it may require adaptation to Nepal's evolving political, economic, and technological context.

Thirdly, the paper does not fully describe the issues regarding institutional and behavioral barriers into energy transitions, like how public will react to new technologies, market readiness of biofuels, or the challenges to implement waste segregation and carbon pricing. Thus, these social and political angles are very important for real world adoption but are not discussed in the present study.

Finally, the research is limited by the lack of pilot project data from Nepal in hydrogen, CCU or large-scale waste to energy applications. Therefore, future work should emphasize demonstration of the projects and field studies in order to validate technical feasibility, financial competitiveness, and social acceptance in Nepalese scenario.

Because of these limitations, the study highlights the need for more targeted research, primary data collection and cross-sectoral engagement in order to improvise and operationalize the pathways presented here.

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