International Journal of Sustainable Progress
Volume 4, Issue 1, June 2025
https://ijsp.globalpublisher.org/
https://globalpublisher.org/journals-1001/

Cost-benefit analysis of energy transition: challenges, clean energy investment, and economic implications

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ABSTRACT

The transition from fossil fuels toward energy systems based on renewable resources represents one of the most complex challenges facing the global economy in the twenty-first century. This paper examines the cost and benefit dimensions of this transition, with a focus on necessary investments in clean technologies and their macroeconomic effects. Findings indicate that although upfront investment costs in renewable energy are high, long-term operational cost reductions, decreased pollution, and improved energy security render such investments economically justifiable. Economic modeling suggests that scenarios involving increased shares of renewable energy can significantly reduce carbon emissions while simultaneously promoting GDP growth and reducing fossil fuel dependency. Nevertheless, challenges such as high capital costs in emerging economies, the need for energy storage infrastructure development, and inequality in access to clean investment represent serious barriers along the transition pathway. The results underscore the necessity of designing intelligent fiscal and regulatory policies to facilitate a just and efficient energy transition.

Keywords: Energy transition, cost-benefit, clean investment, renewable energy, carbon economy, energy policy, cost of capital analysis

1. INTRODUCTION

The energy sector plays a pivotal role in the modern economy while simultaneously accounting for a major share of greenhouse gas emissions. Approximately three-quarters of greenhouse gas emissions in the European Union originate from fossil fuel combustion . This reality has elevated the imperative of transitioning toward low-carbon energy systems to a top global policy priority. However, the economic dimensions of this transition—including investment costs in clean technologies, the gradual decommissioning of fossil assets, and effects on economic growth, employment, and social welfare—demand rigorous, evidence-based investigation. Energy transition is not merely a substitution of one energy source for another; it entails a fundamental transformation of infrastructure, supply chains, labor markets, and consumption patterns. In this process, accurate cost-benefit assessment, identification of barriers and opportunities, and optimal pathway design are of critical importance. Countries with different income levels and conditions face distinct challenges in attracting clean energy investment. This paper aims to provide a comprehensive picture of the economic challenges and opportunities of energy transition through a systematic review of contemporary scientific findings and a multi-dimensional cost-benefit analysis. It seeks to answer the question of how clean energy investment potential can be harnessed to achieve sustainable economic growth while mitigating adverse environmental impacts.

2. MAIN BODY

2.1 Cost of Capital and Investment Challenges in Emerging Economies

One of the primary barriers to energy transition is the deep gap in the cost of capital for clean energy projects across different regions of the world. As a key component determining the levelized cost of energy, the cost of capital is influenced by factors such as perceived investment risks, economic stability, and the quality of financial institutions. Studies show that the cost of capital for renewable projects in emerging and developing economies is significantly higher than in developed countries . This inequality in financing conditions diverts clean investment flows toward lower-risk regions and constrains the share of developing countries in such investments. The factors affecting the cost of capital for renewable energy projects are summarized in the following table:

Table 1: Factors influencing the cost of capital for renewable energy projects. This table summarizes the key determinants affecting the cost of capital in clean energy investments, categorized by their mechanism of influence on perceived investment risk and financial returns. Source: Adapted from Nikas et al. (2025)

Factor	Effect on Cost of Capital	Mechanism of Influence
Political and legal stability	Reduces cost	Lowers perceived risk and increases investor confidence
Inflation and exchange rates	Increases cost	Raises price volatility and return uncertainty
Financial and banking market maturity	Reduces cost	Facilitates access to finance at competitive interest rates
Technical expertise and experience	Reduces cost	Lowers execution risk and improves project efficiency
Government incentives and fiscal support	Reduces cost	Reduces risk and enhances economic attractiveness

One proposed policy to bridge this gap is "corrective justice" through taxing windfall profits of fossil fuel companies and allocating the proceeds as subsidies to reduce investment risk in high-risk regions . Such a policy could simultaneously enhance the economic attractiveness of clean projects and promote a fairer distribution of resources, thereby accelerating the global energy transition.

a. Economic Benefits of the Renewable Energy Transition: Empirical Evidence

Despite investment challenges, substantial evidence points to significant economic benefits of transitioning to clean energy. A study employing a dynamic computable general equilibrium (DCGE) model for the Iranian economy shows that a 10% increase in the share of renewable energy in electricity generation could lead to a 3.41% GDP growth over a ten-year horizon . This positive economic outcome is accompanied by reduced fossil fuel demand and increased gas and oil exports due to resource savings—among the key achievements of this scenario.

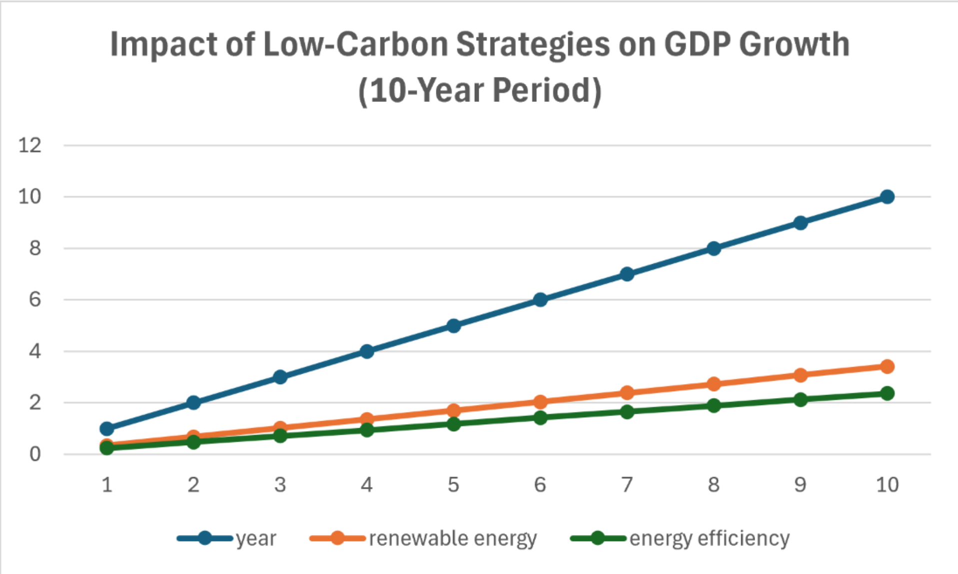

Figure 1: Comparison of the impact of low-carbon strategies on GDP growth over a 10-year period. This line chart illustrates the cumulative GDP growth trajectory under two scenarios: a 10% increase in the share of renewable energy in electricity generation and an improvement in energy efficiency in the power sector. Data are based on simulation results from a DCGE model. Source: Adapted from Ashena et al. (2024)

Another finding is that energy efficiency improvements, while having a smaller economic impact, are more effective from an environmental perspective and can substantially reduce fossil fuel demand and carbon emissions . In other words, a smart combination of renewable energy development and energy efficiency improvements can maximize environmental benefits while preserving economic growth.

2.3 Technical and Economic Challenges on the Path to Full Transition

Despite clear advantages, achieving a fully fossil-free energy system entails profound technical and economic challenges. A study of energy transition scenarios in the European Union shows that in the least‑cost pathway to net‑zero, fossil fuel consumption declines by up to 90% .

However, complete phase-out of fossil fuels—especially in sectors such as chemicals, aviation, and shipping—requires large-scale deployment of e-fuels, which significantly increases the marginal abatement cost.

Table 2: Comparison of EU net-zero scenarios in 2050

Indicator	Least-cost pathway	Fossil-free scenario
Fossil fuel consumption reduction (vs. 2020)	~90%	~99.5%
Electricity share in final energy	~60%	~60%
Variable renewable share in electricity	Up to 83%	Higher than least-cost
Marginal abatement cost (€/tCO_2)	€460/tCO_2	€630/tCO_2
Dependence on e-fuels	9% of final energy	19% of final energy

This finding indicates that the more ambitious the target for reducing fossil fuel dependence, the more steeply the marginal abatement cost increases. Hence, deciding the ultimate degree of "fossil-free" status is a key cost-benefit question that must consider political, social, and environmental trade-offs.

2.4 Enabling Technologies and Cost Reduction: The Potential of Power-to-X

A key strategy to overcome the economic hurdles of energy transition is the development and deployment of enabling technologies such as Power-to-X (PtX). PtX processes allow the conversion of renewable electricity into chemical energy carriers like green hydrogen, methanol, and synthetic fuels, which can be used in hard-to-abate sectors that are difficult to electrify directly .

Research indicates that optimal siting of PtX facilities has a decisive impact on the levelized cost and carbon footprint of the products. Regions with high wind capacity produce the lowest-cost and lowest-emission products, whereas regions relying solely on solar power exhibit weaker carbon performance due to higher embedded emissions in photovoltaic manufacturing . Furthermore, the use of flexible PtX technologies—which can adapt to the variability of renewable generation—combined with energy storage systems can simultaneously reduce both costs and greenhouse gas emissions.

2.5 System-Level Cost-Benefit Analysis: The EROI Approach

Beyond purely economic cost analysis, assessing the system-wide Energy Return on Investment (EROI) provides a critical metric for evaluating the sustainability of the energy transition. This indicator measures the ratio of energy delivered by a system to the energy consumed in its construction, operation, and maintenance.

Research shows that various net-zero energy transition scenarios all exhibit EROI values above the critical threshold (around 10), indicating positive net energy returns . However, the trajectory of this indicator depends strongly on the transition pathway. As the share of renewables increases and enabling technologies such as large-scale storage and synthetic fuels become necessary, EROI tends to decline. Moreover, shortening the transition period, while achieving climate goals faster, may lead to a steeper decline in EROI . This finding underscores that, alongside cost and emission considerations, the long-term energy return of the system must also be taken into account.

3. RESULTS

Based on the foregoing analysis, the following key results can be derived:

1. Economic Justification of Clean Investment: Despite high upfront costs, investment in renewable energy and energy efficiency is economically viable in the long term, capable of generating GDP growth, reducing fossil fuel dependency, and increasing energy export revenues.

2. Cost of Capital Challenge: Inequality in the cost of capital poses a serious barrier to clean energy deployment in emerging economies, necessitating international policy measures such as investment risk guarantees and equitable financial resource allocation.

3. Increasing Cost of Complete Fossil Phase-out: Achieving very low or zero levels of fossil fuel consumption leads to exponential increases in marginal abatement costs. Thus, target-setting requires careful cost-benefit assessment and prioritization.

4. Role of Enabling Technologies:Technologies such as Power-to-X play a critical role in reducing costs and emissions by converting renewable electricity into carriers usable in hard-to-abate sectors. Appropriate site selection and smart resource combinations significantly affect their performance.

5. Energy Sustainability: The EROI indicator shows that renewable-based systems have positive net energy returns, but these returns decline with higher renewable penetration and the need for supporting technologies.

4. CONCLUSION AND RECOMMENDATIONS

The energy transition is a global necessity and a major economic opportunity, yet its pathway is fraught with complexities and challenges. Cost-benefit analysis indicates that although upfront investment costs in clean energy are substantial, long-term benefits—including pollution reduction, improved energy security, and economic growth—make such investments worthwhile.

To succeed in this endeavor, a comprehensive, multi-dimensional approach is essential, encompassing the following:

- Smart Fiscal Support Policies: Designing targeted incentives, reducing the cost of capital for renewable projects especially in developing countries, and implementing green taxes on fossil fuels to raise necessary funds.
- Investment in R&D: Supporting emerging technologies such as grid‑scale storage, e‑fuels, and green hydrogen to reduce costs and improve efficiency.
- Integrated Long‑Term Planning: Developing national and regional roadmaps that account for local capacities, constraints, and priorities, while balancing environmental, economic, and social objectives.
- International Cooperation: Establishing mechanisms for technology transfer, co‑financing of clean projects, and de‑risking investment in less‑developed regions.

The transition to clean energy is a difficult but unavoidable journey. With careful planning, wise policy‑making, and global cooperation, it can lead to a more sustainable and prosperous future for all.

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