Received: 28 July 2025 | Revised: 11 May 2026 | Accepted: 22 May 2026 | Published online: 18 June 2026

RESEARCH ARTICLE

Green and Low-Carbon Economy
2026, Vol. 00(00) 1–14
DOI: 10.47852/bonviewGLCE62026965
BON VIEW PUBLISHING

Pathways to a Green Transition in Kerala: Economic and Employment Impacts from a State-Level Integrated Assessment

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Abstract: Regional modeling is essential for assessing the impacts of environmental policies in countries with significant regional diversity. It is particularly important for a resource-constrained state like Kerala (India), which depends heavily on electricity imports from other states. The novelty of this study lies in the development of a state-level Integrated Assessment Model (IAM) that links a recursive multi-regional dynamic computable general equilibrium model with a bottom-up energy model, considering region-specific parameters. To the best of our knowledge, such a state-level regional modeling framework for India has not been developed in the existing literature, thereby addressing an important research gap in assessing region-specific pathways and policy impacts. This paper explores the economic and employment implications of the green transition for Kerala. The contributions to the literature are (a) regional modeling; (b) a framework and assessment of the impact of green transition considering the interlinkage between the state, the rest of India, and the rest of the world; and (c) estimation of required investment and effect on employment generation. The findings suggest that reducing fossil electricity imports without expanding renewable energy infrastructure may constrain economic growth (Policy Scenario 1). In contrast, investments in local renewable energy capacity through revenue recycling, along with improvements in energy efficiency and productivity (Policy Scenario 2), can enhance economic returns and generate more employment. There is an increase in real state domestic product, consumption, investment, returns to factors, and employment in Policy Scenario 2 as compared to the baseline and Policy Scenario 1. Both final energy requirement for fossil fuel and emissions are also lower in Policy Scenario 2. Energy efficiency can be enhanced through investments in efficient technologies, smart grids, low-emission transport systems, and modern energy infrastructure. Productivity improvements require skill development, innovation-oriented policies, and support for entrepreneurship. Green transition also presents an opportunity for Kerala to strengthen energy security through the expansion of renewables.

Keywords: Integrated Assessment Model, subnational-level CGE modeling, energy system modeling, green transition, employment

1. Introduction

Regional modeling plays a pivotal role in shaping effective policy strategies concerning economic development and environmental sustainability. By analyzing regional models incorporating regional data, policies, and the linkage between regions and sectors, policymakers can identify region-specific opportunities and challenges. Such models require to capture climate–energy–economy interactions, considering both detailed insights into energy technologies and emissions, and economy-wide consistency, capturing inter-sectoral interactions, price effects, and feedback loops. This regional analysis is especially critical while implementing broad national or global sustainability targets, such as the energy transition.

At the 28th session of the Conference of the Parties (COP28) held in Dubai, there was a consensus among participating nations that a transition away from fossil fuels within energy systems must proceed in a just, orderly, and equitable manner. In response to global climate imperatives, India declared its intention at COP26 to achieve net-zero greenhouse gas emissions by 2070. This commitment is complemented by intermediate targets under the country's Nationally Determined Contributions, including a 45% reduction in emissions intensity relative to GDP from 2005 levels by 2030 and securing 50% of installed electric power capacity from non-fossil fuel sources by the same year. Achieving these targets requires not only national-level action but also a thorough understanding of implications at the subnational level. This study focuses on assessing the economic, energy, and employment

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impacts of green transition in the Indian state of Kerala, with particular emphasis on the development of renewable energy infrastructure.

Kerala, located along India's western coast, exemplifies a region facing significant challenges in energy security. The state doesn't meet its electricity demand from internal generation and remains heavily reliant on imported electricity from other Indian states. Consequently, Kerala's energy transition cannot be viewed solely through the lens of national or global climate objectives. Instead, it presents a unique opportunity for the state to enhance energy self-sufficiency while contributing to broader decarbonization goals. Despite having relatively low per capita emissions, Kerala has experienced an increasing frequency of climate-induced extreme events, such as floods and cyclones, making climate adaptation and mitigation a central concern in the state's policy discourse. This study aims to examine feasible policy alternatives for a low-carbon transition in Kerala's power sector.

The transition to a low-carbon economy is known to exert far-reaching impacts across sectors, including economic growth, employment, energy trade dynamics, environmental quality, and public health [1, 2]. However, these effects are not uniform across regions. For instance, Ordonez et al. [3] demonstrate significant regional variation in employment outcomes resulting from energy transitions. There is broad agreement that transitioning to low-carbon energy systems is vital for addressing climate change, conserving ecological systems, and building a sustainable economy. By adopting renewable energy and sustainable practices, nations and regions can mitigate pollution, conserve finite resources, and generate employment opportunities. However, the economic framework for managing such transitions, particularly at the regional level, remains inadequately explored. Most existing models operate at the national scale and therefore fail to capture the heterogeneity of regional conditions. In the context of India's significant socio-economic and geographic diversity, region-specific assessments are indispensable.

This study aims to bridge this gap by examining feasible policy alternatives for a low-carbon transition in Kerala's power sector. To do so, we utilize an Integrated Assessment Model (IAM) framework that links a computable general equilibrium (CGE) macroeconomic model with a bottom-up energy system model. While such integrated models have been applied in several developed countries, their application in India, particularly at the subnational level, is limited. Given Kerala's reliance on electricity imports and its unique socio-economic structure, a regionally tailored approach is essential.

A core focus of this research is to evaluate the economic implications of a hypothetical ban on electricity imports into Kerala. We aim to determine whether such a constraint could hinder economic growth or, alternatively, catalyze local renewable energy development and job creation. The findings are expected to inform whether a green transition in Kerala can simultaneously achieve environmental goals and stimulate inclusive economic development. Moreover, the study emphasizes the need for state-specific solutions, especially in a federal structure like India's, where natural resource endowments and socio-economic contexts vary widely across states.

In sum, this research underscores the significance of regional modeling in the design and implementation of low-carbon strategies. By contextualizing the green transition within the specific economic and energy landscape of Kerala, it provides valuable insights for policymakers aiming to achieve climate objectives without compromising economic resilience or employment generation.

2. Review of Literature

Given India's commitment to achieving net-zero emissions, states must take proactive steps to reduce their carbon footprint. However, the economic implications of this transition and the most effective policy frameworks remain subjects of ongoing debate. A broad strand of literature examines the policy instruments that can facilitate green transitions, with particular focus on fiscal measures, market-based mechanisms, and technology support policies.

A large body of research highlights the importance of carbon pricing instruments and complementary climate policies in reducing emissions. Several studies demonstrate that carbon pricing and emissions trading schemes (ETS) can be effective tools for mitigating greenhouse gas emissions when implemented alongside other supportive policies [4, 5]. For instance, research shows that policy instruments targeting emissions coverage alone may have limited effects on energy-intensive sectors, whereas combining these measures with ETS can generate stronger synergistic effects [6]. Similarly, carbon taxes accompanied by complementary policies—such as the phase-out of coal-fired power plants or subsidies for nonconventional renewable energy—have been found to produce greater emissions reductions compared to standalone carbon pricing mechanisms [7]. Other studies highlight the role of technological solutions, such as Carbon Capture, Utilization, and Storage (CCUS), when combined with renewable energy expansion to help the power sector achieve emission reduction targets [8]. Improvement of energy efficiency is required to fill the gap between electricity demand and supply [9].

Despite this broad agreement on the importance of climate policy instruments, the literature reveals divergent views regarding their economic impacts. Several studies suggest that carbon taxes may impose negative macroeconomic effects, including reductions in GDP or economic output [10–12]. However, other research indicates that well-designed policy packages can mitigate or even reverse these adverse impacts. For example, the combination of carbon taxes with research and development subsidies can stimulate innovation and promote economic growth while limiting emissions. Empirical evidence also shows that allocating carbon tax revenues toward renewable energy development or productive investments can significantly improve environmental outcomes while offsetting economic costs [13]. Similarly, studies on revenue recycling mechanisms suggest that reinvesting carbon tax revenues into productive sectors or social programs can partially compensate for the economic burden of climate policies [14, 15]. In the context of India, research has shown that directing carbon tax revenues toward productive investments can support inclusive green growth while mitigating the economic impacts of climate policies [16].

Another important strand of literature focuses on modeling approaches used to evaluate environmental policies and energy transition pathways. CGE models have been widely employed to assess the economy-wide impacts of mitigation policies in both static and dynamic frameworks [11, 17, 18]. CGE models are also frequently integrated into Integrated Assessment Model (IAM), which combine economic modeling with energy system and climate models to evaluate long-term policy scenarios [19]. For example, several studies have applied integrated modeling frameworks such as Asia-Pacific Integrated Model (AIM)/CGE combined with GAINS, MESSAGEix-GLOBIOM, GCAM, and REMIND-MAgPIE to analyze global and national decarbonization pathways [20–26]. These approaches allow researchers to capture interactions between technological change, energy systems, and macroeconomic dynamics.

Within the Indian context, however, applications of CGE and IAM frameworks remain relatively limited. Existing studies suggest that combining technological advancements with carbon pricing can reduce emissions while sustaining economic growth [27, 28]. Other research highlights the potential of carbon tax recycling mechanisms to promote inclusive green growth and support sustainable development [16]. Integrated modeling studies for India further demonstrate that a low-carbon transition, despite requiring substantial investment, may not hinder economic growth and can even generate economic benefits through technological innovation and improved environmental performance [2, 29]. Additional studies emphasize broader co-benefits such as employment creation, reduced energy imports, and improved air quality resulting from structural changes in the energy sector [1].

Despite these advances, most IAM-based analyses remain focused on national-level assessments, often overlooking regional heterogeneity in economic structures, energy demand patterns, and resource availability. This limitation has led researchers to highlight the importance of regional or subnational modeling frameworks. Existing subnational studies have largely been confined to CGE modeling alone [30]. Regional CGE models, which extend standard CGE frameworks to capture spatial economic interactions, provide more detailed insights into policy impacts on local economies [31, 32]. Such models are particularly important because aggregate national results may mask regional disparities and distributional consequences of technological transitions [33]. Evidence from international studies supports this argument. For example, a multi-regional dynamic CGE analysis covering China's provinces found that subnational climate policies may lead to emission leakage across regions [34]. Other studies highlight the importance of coordinated energy transitions across different technologies and regions to maximize policy synergies [35]. However, comparable regional IAM studies remain scarce in the Indian context.

At the same time, a growing body of research has begun to examine state-level energy transitions in India, particularly through sectoral analyses, policy reports, and electricity system modeling. Several studies have explored renewable energy deployment and power sector transformation across Indian states. For example, analyses of Tamil Nadu suggest that wind capacity could double to around 15 GW while solar capacity may increase significantly under current policy and cost trends [36]. Similarly, projections for Gujarat indicate that renewable energy could account for nearly 70% of installed generation capacity by 2030, highlighting both opportunities and financial risks associated with thermal power assets [37]. Research on Rajasthan also projects a substantial shift toward renewable energy, with renewables potentially accounting for around 74% of installed capacity by 2030 [38]. In another study focusing on Maharashtra, open-source modeling of electricity systems suggests that achieving a 50% renewable energy share by 2030 is technically feasible and economically viable [39]. While these studies provide important insights into state-level renewable energy transitions, they generally focus on power sector modeling and lack an integrated macroeconomic perspective.

These gaps are particularly relevant for analyzing the energy transition of Kerala. The state has a distinctive development profile characterized by high human development indicators, relatively low industrial intensity, and a strong dependence on electricity imports from other regions. At the same time, Kerala has adopted proactive climate policies and faces high vulnerability to climate-related risks, making it a relevant case for examining low-carbon transition pathways at the subnational level.

To date, there has been limited research examining the regional economic and employment impacts of energy transitions in India using integrated macro-modeling approaches. Existing subnational studies have largely relied on either sectoral analyses or standalone CGE frameworks. This study contributes to the literature by developing an integrated modeling framework that combines a recursive dynamic CGE model with a bottom-up energy system model (MESSAGEix) at the subnational level. Using Kerala as a case study, the model evaluates the investment requirements and employment implications of renewable energy transitions in the power sector. To the best of the authors' knowledge, this study represents the first regional integrated CGE–energy system modeling framework applied to India.

3. Methodology: Modeling Framework and Simulation Design

Our study uses an IAM, which comprises a top-down CGE macro model and a bottom-up energy (MESSAGEix) model. The advantage of the CGE model is that it considers the interdependencies between different sectors, agents, and markets in the economy and, hence, enables us to understand the wider economic impact of policies. Capturing both the economy's supply and demand sides, it allows for an adjustment in both quantities and prices following a policy shock. Unlike partial equilibrium models, which concentrate on one section of the economy only, CGE models consider the entire economy and capture the interactions between different sectors, agents, and markets of the economy. The model explicitly includes supply and demand equations for every sector, ensuring endogenous determination of price and output. Generally, the supply function depends on labor, capital, and intermediate inputs, along with their prices, whereas the demand function considers prices, agents' preferences, income, etc. Because of its flexibility, the models can be used to simulate various policies and shocks.

The CGE framework in this study is a recursive dynamic multi-region model for the state of Kerala. As Kerala, a state in India, is small in size, its economy is influenced by economic linkage with the rest of India and the world. So, the modeling framework must account for this using a multi-region modeling tool. The CGE model generates baseline and policy estimates for prices and output (sector-wise GDP), while the bottom-up model identifies optimal technology options from available bundles, utilizing resources most cost-effectively. It also provides the investment figures required to implement these technologies. These investment figures are fed back into the CGE model for verifying whether the growth path deviates. Such an iterative two-way feedback process is continued till GDP numbers in successive rounds are found to be converging.

3.1. Modeling framework of CGE model

A CGE model is a quantitative framework used to represent how an entire economy functions and responds to policy changes or external shocks. It captures the interactions among households, firms, government, and the rest of the world, ensuring that all markets, that is, goods, factors of production, and trade, clear simultaneously. Producers are modeled as maximizing profits subject to technology constraints, while households maximize utility given their income and prices. The model is calibrated using a consistent database, which reflects the structure of the economy in a benchmark equilibrium. CGE models are widely used to analyze policy issues such as taxation, trade reforms, environmental regulations, and energy transitions because they account for economy-wide linkages, feedback effects, and resource constraints. By simulating how prices, production, consumption, and trade adjust across sectors, CGE models provide insights into the macroeconomic indicators. The mathematical description of the model is as follows.

This study employs the GTAP-Power CGE model, which extends the standard GTAP framework by incorporating detailed representations of the electricity sector. The electricity sector is disaggregated into multiple generation technologies, with production modeled using a nested Constant Elasticity of Substitution (CES) structure. At the first level of nesting, total electricity output (Q_E) is produced by aggregating the outputs of individual generation technologies (Q_i) through a CES function:

$$Q_E = \left(\sum_i \alpha_i \cdot Q_i^{\rho} \right)^{1/\rho}$$

Here, α_i denotes the share parameter calibrated for each generation technology i, and ρ is the CES substitution parameter, related to the elasticity of substitution by $\sigma = 1/(1-\rho)$. Further nested levels categorize generation technologies into fossil-fuel-based and low-carbon groups, each with its own elasticity parameter, reflecting different degrees of substitutability within and between groups.

Electricity market equilibrium is achieved when total supply from all generation technologies equals aggregate demand (DE), which contains both final demand and intermediate uses:

$$\sum_i Q_i = D_E$$

Final demand for electricity and other goods is shown using a CES utility function:

$$U = (\alpha_E \cdot Q_E^{\sigma} + \alpha_o \cdot Q_o^{\sigma})^{1/\sigma}$$

where Q_E represents electricity consumption, Q_O stands for the composite of other goods, and σ denotes the elasticity of substitution between electricity and other consumption categories.

The composite electricity price P_E is estimated using the CES aggregation of technology-specific prices P_i:

$$P_E = (\sum_{\mathrm{i}} \alpha_i \cdot P_i^{1-\rho})^{1/(1\text{-}\rho)}$$

This captures cost variations across generation technologies, including differences in fuel prices, taxes, and subsidies. Power sector emissions are calculated by multiplying the output of each technology by its emissions coefficient β_i:

$$E = \sum_i \beta_i \cdot Q_i$$

Policy instruments like carbon taxes are incorporated by adjusting generation costs for carbon-intensive technologies, proportional to their emissions:

$$C_i^{adj} = C_i + \tau \cdot \beta_i$$

where C_i is the base generation cost, τ is the carbon tax rate, and β_i is the emissions factor for generation technology i.

The model is calibrated using the GTAP-Power database for a selected base year. Share parameters (α_i) are based on observed generation shares, while substitution elasticities are drawn from empirical literature to reflect realistic technological and economic substitution patterns. Observed emissions data and generation outputs (Q_i) are utilized to calibrate emissions coefficients β_i.

Generation prices P_i are determined by input costs, including capital, fuel, labor, taxes, and operational expenses, ensuring consistency with the benchmark data. This nested CES framework, combined with empirically grounded elasticities and detailed policy modeling, allows GTAP-Power to assess the effects of energy and climate policies, fuel price shifts, and technological transitions within an interlinked global market.

Calibration in a model means setting it up so that it matches the real-world economy at a starting point (the base year). This is done by using actual data on production, consumption, trade, and prices. In short, calibration ensures that the model begins from a realistic and internally consistent benchmark. Dynamic adjustment refers to how the model shows changes over time. As the economy evolves, investment adds to the capital stock while depreciation reduces it, allowing industries to expand or contract gradually.

3.2. Modeling framework of MESSAGEix model

The MESSAGEix model is a dynamic, bottom-up energy systems model used to analyze long-term energy planning and policy pathways. It represents the entire energy system, from resource extraction to final energy use, by explicitly modeling technologies, fuels, and their interactions over time. The model determines the least-cost combination of technologies and energy flows needed to meet specified demands, subject to constraints such as resource availability, technological capacities, and environmental limits (e.g., emissions targets). Widely used for climate and energy policy analysis, MESSAGEix helps evaluate scenarios related to energy transition, decarbonization, and sustainability by capturing technological detail and intertemporal decision-making.

MESSAGEix model is a linear programming-based, bottom-up, technology-rich optimization framework designed for long-term energy system planning. MESSAGEix identifies cost-optimal energy system pathways by minimizing the total discounted system cost over a multi-period planning horizon. The optimization is subject to a range of technical, economic, and policy constraints. The objective function can be defined as:

$$\mathit{Minimize}\colon\ Z = \sum_t \sum_r \frac{1}{(1+d)^t} \left(\sum_a C_{a,r,t} \cdot ACT_{a,r,t} + \sum_c C_{c,r,t} \cdot CAP_{c,r,t} \right)$$

where $C_{a,r,t}$ represents activity costs and $C_{c,r,t}$ represents investment costs discounted at a rate d, and together, they represent total system costs. $ACT_{c,r,t}$ is the activity level of technology a. $CAP_{c,r,t}$ is the installed capacity of technology. The model enforces energy balance constraints for each commodity, region, and time period, ensuring that supply equals demand:

$$\sum_p \eta_{p,a} \cdot ACT_{a,r,t} = D_{p,r,t}$$

with $\eta_{p,a}$ representing output/input coefficients and $D_{p,r,t}$ the final demand. Technology activity is bounded by available installed capacity and its associated capacity factor CF:

$$ACT_{a,r,t} \leq CAP_{a,r,t} \cdot CF_{a,t}$$

Installed capacities evolve dynamically over time through a capital stock rollover equation:

$$CAP_{a,r,t} = CAP_{a,r,t-1} \cdot (1-\delta_a) + CAP\_NEW_{a,r,t}$$

where δ_a is the depreciation rate. Resource availability constraints ensure that resource use does not exceed availability:

$$\sum_a RES_{p,a,r,t} \cdot ACT_{a,r,t} \leq R_{p,r,t}$$

with $R_{p,r,t}$ as the maximum available resource. Environmental constraints are imposed through emission limits, ensuring technology-specific emissions do not exceed policy thresholds:

$$EM_{e,r,t} \leq EM\_LIMIT_{e,r,t}$$

Cross-border energy trade is restricted by infrastructure limits:

$$\sum_{r'} TRADE_{p,r,r',t} \leq T_{p,r,r't,t}$$

This comprehensive formulation enables MESSAGEix to generate feasible, least-cost energy system transition pathways that align with demand projections, resource endowments, environmental goals, and infrastructure constraints.

3.3. Soft-linking MESSAGEix with GTAP-Power

To incorporate macroeconomic feedbacks into detailed electricity sector planning, this study soft-links the MESSAGEix and GTAP-Power models via investment flows. MESSAGEix, as a bottom-up energy optimization model, determines technology-specific capacity expansion pathways that minimize total system costs. The optimized investment objective is expressed as:

$$Z = \sum_t \sum_r \frac{1}{(1+d)^t} \left(\sum_a C_{a,r,t} \cdot ACT_{a,r,t} + \sum_c C_{c,r,t} \cdot CAP\_NEW_{c,r,t} \right)$$

The critical output for model linkage is the investment requirement for each electricity generation technology:

$$INV^{MSG}_{i,r,t} = C^{\mathrm{INV}}_{\mathrm{i,r,t}} \times CAP\_NEW_{i,r,t}$$

where $C^{INV}_{i.r.t}$ denotes capital cost per unit of capacity for technology i and $CAP\_NEW_{i,r,t}$ is the optimal new capacity addition in region r and time period t.

These disaggregated investment values from MESSAGEix are aggregated and mapped to the electricity sector investment category in the GTAP-Power CGE model. This process updates the CGE model's demand for capital goods and other inputs associated with power generation:

$$I^{GTAP}_{E,r,t} = \sum_i INV^{MSG}_{i,r,t}$$

Through this soft-linking approach, the integrated framework captures both the granular, technology-specific insights of energy system optimization and the economy-wide interactions captured by the CGE model, enabling a more comprehensive assessment of energy and climate policy impacts. A soft link between a CGE model and the MESSAGEix model through investment involves an iterative exchange of information rather than full integration. In this approach, the MESSAGEix model determines the optimal energy system configuration and associated investment requirements under given policy or technology scenarios. These investment projections are then fed into the CGE model as exogenous shocks or sector-specific capital formation, influencing production, prices, and income across the economy. In return, the CGE model can provide updated macroeconomic variables, such as GDP growth, sectoral demand, or energy prices, which are used to adjust energy demand or constraints in MESSAGEix. This back-and-forth process continues until results converge, allowing the analysis to capture both technological detail from the energy system and economy-wide feedbacks from the CGE framework while maintaining model independence.

Our CGE model focuses on energy and the associated sector, and we have aggregated and disaggregated sectors based on that to capture the energy demand and supply factors in the model. In our CGE model, we have divided the state economy into 49 industries, and 49 goods and services are produced. Of these industries, 13 industries are related to the energy sector, depending on the commodity they produce: 3 to primary fuels, that is, coal, oil, and gas, 1 to refined oil, and 8 to electricity generation industries. There is also one sector that includes power distribution and transmission. These power generation industries indicate the primary source of fuel: electricity–nuclear considers nuclear-operated power plants; electricity–gas contains plants using turbines, cogeneration, and combined cycle technologies by combusting gas; electricity–coal produces electricity from coal; electricity–hydro includes hydro generation; electricity–wind implies renewable wind generation; electricity–solar covers photovoltaic (PV) systems; electricity–oil generates electricity from oil sources; and the rest of the electricity generation sectors are clubbed under "other renewables." Apart from these, 13 major energy-intensive industries are modeled separately. We have also considered different modes of transport: land transport (passengers and freight transport by road/rail), air transport, and water transport (by boat or ship for sea, river).

Our model, a multi-region model patterned after GTAP-power, defines the region as Kerala, the rest of India, and the rest of the world and considers trade among regions in commodities/services. For the purposes of this analysis, we assume that electricity trade occurs exclusively between Kerala and the rest of India. The demand projections, derived in the CGE model, are used as exogenous input to the bottom-up MESSAGEix model. The supply side in the MESSAGEix model meets projected demands using an optimization approach that prioritizes least-cost system expansion. This optimization operates within various policy constraints, including environmental, resource, and capacity limitations. In our CGE model, price is endogenously determined, and the broad price level is used as an input to the MESSAGEix model. The energy sector prices in the MESSAGEix model are calibrated from past data by synchronizing with the broad price level.

The CGE model employed is a recursively dynamic framework, solved through a sequence of static, single-year CGE simulations. Sector-specific capital stocks and labor availability are treated as exogenous inputs at the beginning of each period. Capital accumulation in each sector occurs between periods, driven by investment activities undertaken during the preceding period. The investment rate is typically considered to be endogenously determined by market forces, particularly the anticipated return on investment. Labor force growth is assumed to follow demographic trends.

A dynamic CGE model captures the evolution of an economy over time by linking economic decisions and outcomes across multiple periods. Unlike static models that represent a single year, dynamic CGE models incorporate mechanisms such as capital accumulation, demographic change, and technological progress. Typically solved recursively, one period at a time, these models update variables like capital stock and labor supply based on previous period outcomes. Labor supply is usually tied to population projections, while capital accumulation depends on past investment decisions driven by sectoral profitability. Dynamic CGE models are particularly useful for simulating the long-term impacts of policies or external shocks. Through policy simulation, they can examine how a policy introduced in one period, like a renewable energy subsidy, affects sectoral output, factor allocation, emissions, and income distribution over time. The impacts of a policy are reported as percentage deviation from the baseline forecast.

In this study, we develop a dynamic macroeconomic CGE model to assess the implications of low-carbon policy interventions on Kerala's economy. Two plausible policy scenarios are formulated to examine their effects on the macroeconomy, sector-specific outcomes, investment requirements, and emissions. A baseline simulation serves as a reference point for comparison with the alternative policy scenarios.

3.4. Policy scenarios

1) **Scenario 1: restriction on fossil-based electricity imports**

Kerala currently relies heavily on electricity imports, primarily from fossil fuel-based sources. Baseline simulations project that this trend will continue through 2050. However, as other Indian states transition toward renewable energy, the cost of imported fossil-based electricity may rise, posing economic challenges for Kerala. This scenario explores the impact of imposing restrictions on fossil electricity imports. The aim is to evaluate whether such a policy stimulates local renewable electricity generation or increases the share of renewable imports from other states.

2) **Scenario 2: scenario 1 + renewable capacity augmentation + enhanced energy efficiency**

Building upon Scenario 1, this simulation assumes that 50% of the estimated renewable energy potential, both in Kerala and the rest of India, is realized by 2050. It is assumed that investment funding is not a constraint. Additionally, energy efficiency improves at a rate of 2.5% annually, aligned with the Energy Efficiency Outlook for India by the International Energy Agency, which estimates a 19% improvement in energy intensity by 2040. Additionally, a uniform 1% annual total factor productivity (TFP) growth across all sectors is assumed, consistent with historical TFP performance in India [40, 41].

3.5. The database

Our CGE model is calibrated to a benchmark equilibrium dataset representing the Kerala economy for the year 2021. The primary data source is a custom-built Kerala input–output table, constructed specifically for this study using the methodology proposed by Pal et al. [42]. In addition to the input–output framework, the model requires a range of behavioral parameters and elasticities, which are sourced from relevant empirical studies, with an emphasis on India-focused literature [42, 43]. Sectoral productivity estimates are compiled from a combination of Indian studies and the India KLEMS database published by the Reserve Bank of India for various years.

Demographic data are obtained from the Census of India, with national and state-level population projections beyond 2036 drawn from the UN Population Projections (2022). Labor supply projections for Kerala are derived using Labor Force Participation Rates, while the national-level labor supply is constructed based on demographic trends.

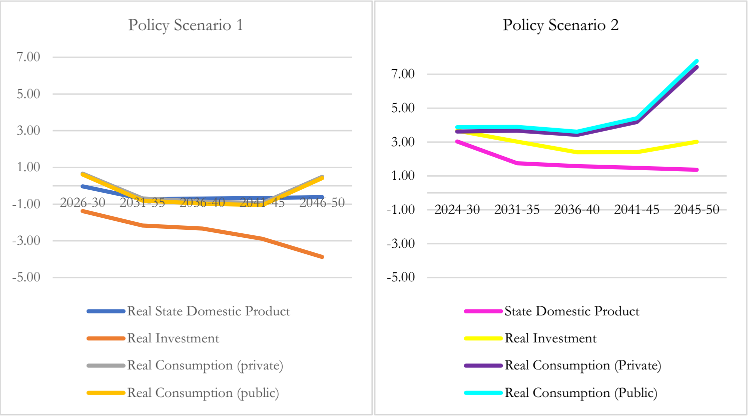
The CGE model generates a sequence of equilibria from 2021 to 2051, incorporating both state-specific and country-level dynamics. This framework allows for the simulation of growth trajectories for key macroeconomic variables under both baseline and policy scenarios over a 30-year horizon (2021–2050). For the energy system component, the model incorporates various renewable energy and efficiency targets outlined in official planning documents from the Government of Kerala and the Government of India.

4. Result

4.1. Macroeconomic results

Figure 1 presents the trajectory of selected variables influencing real state domestic product (SDP) under Policy Scenarios 1 and 2, expressed as deviations from the baseline scenario. In Policy Scenario 1, real SDP consistently deviates negatively from the baseline across the entire simulation period, indicating a sustained decline in economic output. This downward trend reflects the cumulative effect of a progressive restriction on the import of fossil fuel-based electricity. The decline in real SDP is primarily driven by negative deviations in labor and capital utilization,

Figure 1
Macroeconomic indicators of Kerala (percentage derivation from baseline)



as well as in TFP. Given that energy is a critical input across all production sectors, limiting access to fossil-based electricity leads to widespread disruptions in industrial activity, resulting in reduced output across sectors and a contraction in overall economic performance.

Improving energy efficiency is a critical component of transitioning to a low-carbon development pathway, and India has made notable progress in this area over the years. In Policy Scenario 2, we assume an annual autonomous energy efficiency improvement of 2.5% across all energy sectors, a target considered both ambitious and achievable. Additionally, we incorporate a 1% annual growth in TFP, consistent with historical performance, as India has previously recorded TFP growth rates exceeding this threshold. These shocks are applied uniformly to both Kerala and the rest of India.

This scenario is implemented in conjunction with the assumptions of Scenario 1, namely, the restriction on fossil-based electricity imports into Kerala, and further includes the augmentation of renewable electricity capacity in both Kerala and other Indian states. As shown in Figure 1, real SDP under Policy Scenario 2 demonstrates a positive deviation from the baseline, indicating that efficiency improvements and renewable energy expansion can more than offset the adverse impacts of fossil fuel restrictions. In the expenditure approach of GDP, the augmentation of electricity capacity boosts investment, leading to an increase in consumption expenditure. This is also reflected in the income side of the GDP components. The disaggregated components of SDP, such as sectoral output, capital formation, and employment, also exhibit positive growth trends, as illustrated in Figure 2. In Policy Scenario 1, there is a negative deviation in policy scenario as compared to baseline in returns to all the components like skilled and unskilled labor and capital, reflecting the reduction in the returns in Policy Scenario 1 as compared to baseline. On the contrary, Policy Scenario 2 shows a positive deviation from the baseline, signifying that under Policy Scenario 2, there is an increase in returns to factors as compared to the baseline.

4.2. Effects on energy demand, fuel mix, and emission

As shown in Figure 3, final energy demand in the transport and industry sectors is significantly lower under Policy Scenario 1 compared to the baseline. This reduction primarily results from decreased economic activity driven by restrictions on fossil-based electricity imports under Scenario 1. However, in Policy Scenario 2, which includes interventions on the renewable energy front, final energy demand in the transport sector increases relative to Scenario 1—despite some moderation due to efficiency gains. This suggests that renewable energy expansion and improved productivity stimulate economic activity, thereby raising energy requirements in the transport sector. In the industry sector, however, final energy demand decreases in Policy Scenario 2 as compared to Baseline or Policy Scenario 1 due to efficiency and productivity gains.

With improvements in energy efficiency and TFP, in the final fuel mix, the demand for oil declines most sharply in Policy Scenario 2 as compared to the baseline scenario (Figure 4), followed by reductions in the consumption of electricity and biofuels. The model also incorporates a variety of alternative fuel mix technologies, including biogas, biomass, off-grid wind electricity, solar thermal, green hydrogen, and solar off-grid electricity across

Figure 2
Average year-wise real return of all factors (percentage deviation from baseline)

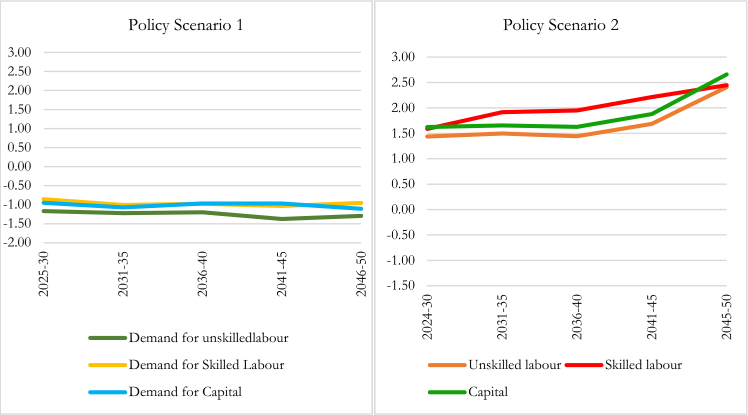


Figure 3
Final energy requirement

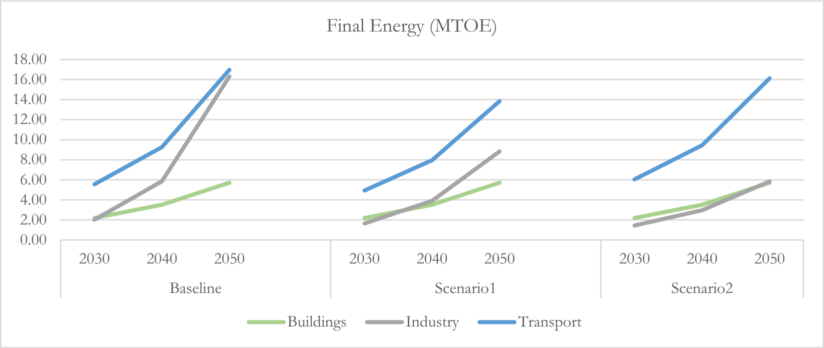
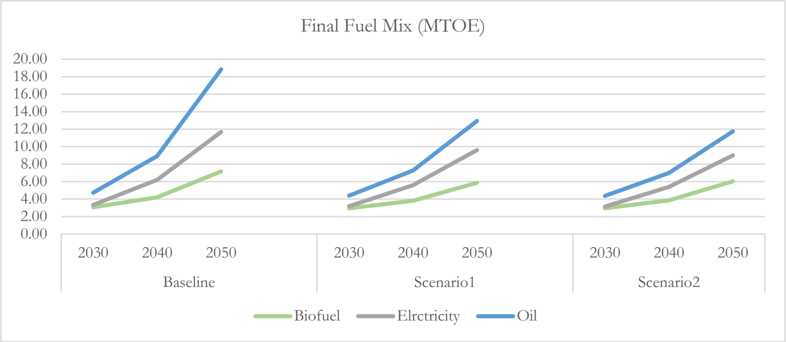


Figure 4
Final fuel mix



the baseline and policy simulations. However, only biogas, green hydrogen, and solar off-grid electricity register marginal increases under Policy Scenario 2, while the remaining technologies do not show any presence in either the baseline or Scenario 2 outcomes.

Kerala's economic structure is distinct from many other Indian states, with a relatively small industrial base and a service-led growth trajectory, particularly driven by the tourism sector. As a result, the state's per capita greenhouse gas emissions are considerably lower—0.09 tCO_2e per capita in 2018—compared to the national average of 2.24 tCO_2e per capita. A key factor contributing to Kerala's low emissions is the limited share of the power generation sector in the state's total emissions. This can be attributed to two main reasons. First, Kerala imports a substantial share of its electricity; in 2018, 66% of the electricity procured by the Kerala State Electricity Board was purchased at the delivery point and not generated within the state. Second, the state's electricity mix is dominated by renewable sources: hydropower accounts for approximately 85%, followed by small hydro (8.5%), solar (4.5%), and wind (1.2%). The minimal reliance on thermal power generation further contributes to Kerala's relatively low emissions from the energy sector.

Figure 5 presents the per capita and overall emission levels for the baseline and Policy Scenario 2 for selected sectors. Under the low-carbon transition in Scenario 2, per capita emissions decline markedly—from 3.73 tCO_2e to 2.18 tCO_2e by 2050. The sectoral distribution of emissions is also depicted, showing a notable reduction in industrial emissions, largely driven by energy efficiency gains and a shift in fuel mix. Emissions from oil consumption also decline significantly. Despite the overall decarbonization trend, total emissions under Scenario 2 rise in absolute terms due to economic and population growth, increasing from 22 $MtCO_2e$ in 2025 to 43 $MtCO_2e$ in 2040 and reaching 81 $MtCO_2e$ by 2050.

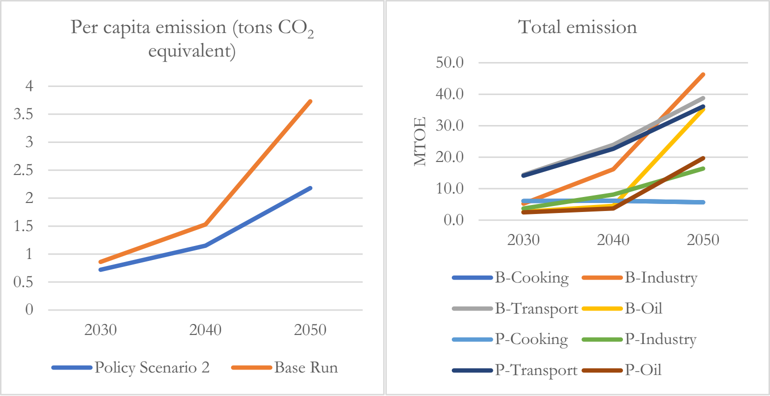
4.3. Implication on employment

As discussed in earlier sections, the adoption of a low-carbon transition pathway for Kerala is expected to significantly alter the composition of energy use across sectors. Since employment intensity varies across energy types, this shift will have important implications for direct employment generation within the energy sector. Additionally, given that power generation relies on inputs from multiple sectors, the inter-sectoral linkages—which differ between fossil-based and renewable energy industries—can further influence employment across the broader economy. These effects are captured through CGE model–derived employment coefficients, which allow us to estimate employment outcomes across policy scenarios.

Mitigation strategies, particularly those involving the expansion of renewable energy infrastructure, create new opportunities for job creation—not only in operation and maintenance (O&M) but also in manufacturing and installation of renewable energy technologies such as solar PV and wind power plants. This section presents employment projections for Kerala under both the baseline and Policy Scenario 2.

According to the Periodic Labour Force Survey (PLFS) 2021–22, Kerala's unemployment rate (based on usual status—principal and subsidiary combined) stood at 9.6%, considerably higher than the all-India average of 4.1% for individuals aged 15 years and above. In this study, employment coefficients have

Figure 5
Emission profile



been derived using PLFS data under the usual status approach. Employment is estimated by capturing the "proximity" of job creation in relation to final energy demand. We define direct jobs as those associated with the O&M of energy infrastructure; indirect jobs as those created in upstream supply chains—for raw material extraction, component manufacturing, construction, and service provision; and induced jobs as employment generated through increased household spending stemming from income earned via direct and indirect employment. All three comprise estimates for total employment.

Employment in the renewable energy sector spans manufacturing, installation, operations, and support services. Major job creation comes from the construction and installation of solar and wind projects, while long-term roles exist in operations and maintenance. Additional employment arises in logistics, finance, and project development, along with high-skill jobs in research and innovation. According to the International Renewable Energy Agency, solar energy generates the largest share of jobs globally, with countries like India benefiting from policy support such as the National Solar Mission. With an increased share of renewable energy in the power sector in subsequent years, there would be more direct employment from operations and management in new power plants, along with jobs in the supply chain of the renewable energy sector (indirect) and through increased expenditure by the people employed in those sectors (induced).

Our simulation results indicate that direct employment from the O&M of power plants under Policy Scenario 2 exceeds the baseline trajectory significantly from 2040 onward. By 2050, the policy scenario is expected to generate an additional 0.8 million direct jobs in Kerala's energy sector (Figure 6). Furthermore, total employment, encompassing direct, indirect, and induced effects, is projected to be 1.1 million higher than the baseline by 2050. The larger gap between total and direct employment reflects the influence of inter-industry linkages, whereby policy interventions in the energy sector stimulate employment in related sectors across the economy.

Investment in renewable energy contributes to employment generation not only through O&M activities but also through the manufacturing and installation of new power plants. To estimate these employment effects, we use the median values of direct employment factors for key deployment phases of wind and solar PV technologies, as reported in Cameron and van der Zwaan [44]. These employment multipliers are applied to the projected capacity additions under Policy Scenario 2.

The results indicate a substantial increase in employment from the renewable energy supply chain under this scenario. Specifically, Policy Scenario 2 is expected to generate approximately 75,000 additional jobs in Kerala by 2050 from the combined effects of manufacturing and installation of renewable energy infrastructure, relative to the baseline scenario (Figure 7).

Figure 6
Change in direct and total employment

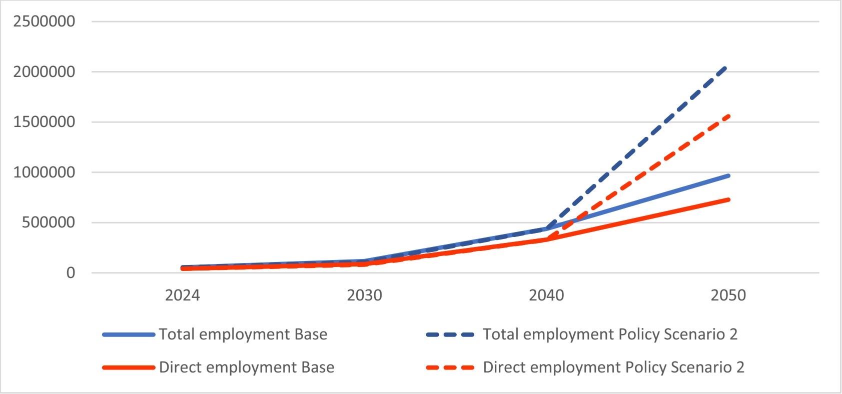
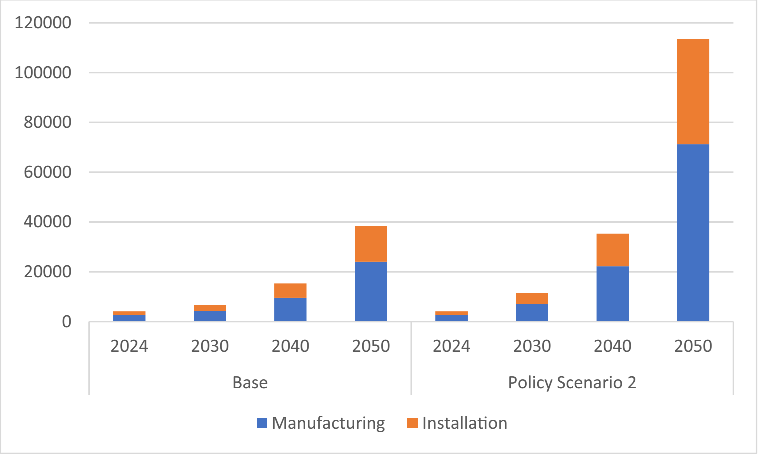


Figure 7
Employment in manufacturing and installation of new renewable power plants



This underscores the potential of clean energy investments to stimulate broader economic development through job creation across multiple stages of the renewable energy lifecycle.

We conducted a sensitivity analysis to assess the robustness of our model results with respect to the following parameters:

1) Increase in energy efficiency
2) Decrease in energy efficiency
3) Faster deployment of renewable energy
4) Slower deployment of renewable energy

We increased each of the parameters by 10% and ran the corresponding baseline scenario and policy scenario and found the difference in outcomes of the two policy scenarios. The percentage deviation of the policy scenario, with the policy scenario with the changed parameters, shows marginal deviation and provides confirmation of the robustness of the results (Table 1).

Table 1
Percentage changes in employment in alternative policy scenarios with changed parameters vis-à-vis policy scenario

	Total employment				Direct employment			
	Sc.: Increased energy efficiency (%)	Sc.: decreased energy efficiency (%)	Sc.: Faster deployment of renewable energy (%)	Sc.: Slower deployment of renewable energy (%)	Sc.: Increased energy efficiency (%)	Sc.: decreased energy efficiency (%)	Sc.: Faster deployment of renewable energy (%)	Sc.: Slower deployment of renewable energy (%)
2024	–0.001	–0.001	–0.001	–0.001	–0.001	–0.001	–0.001	–0.001
2030	–0.001	0.448	–0.058	0.391	0.001	0.451	–0.056	0.394
2040	–1.560	–8.654	–5.262	–2.536	–1.561	–8.697	–5.282	–2.546
2050	3.995	–1.909	–2.399	–0.503	3.997	–1.925	–2.406	–0.505

4.4. Investment requirement for green transition

Table 2 presents the cumulative investment requirements (in US$ million) under the baseline and Policy Scenario 2 for Kerala's low-carbon transition across major sectors between 2025 and 2050. The total investment required under the policy scenario is estimated at US$ 230.75 billion, which is lower than the baseline projection of US$ 262.51 billion. This decline reflects the effects of improved energy efficiency and productivity growth, enabling the state to pursue a low-carbon pathway with reduced investment intensity—from 0.83% of cumulative SDP under the baseline to 0.36% under the policy scenario.

The most notable investment savings occur in transport, particularly passenger transport (US$ 23.5 billion), freight transport (US$ 4.8 billion), and industry (US$ 1.85 billion), reflecting reduced fossil fuel dependence and energy demand. Investment in electricity, buildings, and agriculture remains unchanged, indicating that existing trajectories in these sectors already support low-carbon outcomes. A few emerging technologies like green hydrogen and biogas show marginal reductions in investment. We assume that both Kerala and the rest of India transition toward renewable energy sources in the model. Consequently, the imposed ban on imports of fossil-fuel-based electricity implies that any future electricity imports would be predominantly renewable-based. Given that Kerala's economy is not highly industry-intensive, such renewable electricity imports are expected to be sufficient to meet the state's energy demand. As a result, the additional investment required in Kerala's electricity sector remains relatively modest. Overall, the analysis highlights that Kerala's low-carbon transition can be achieved with lower total investment and a more efficient allocation of resources, making the pathway not only environmentally sustainable but also economically viable.

It is important to note that the estimated investment figures are iteratively fed into the macroeconomic CGE model to assess their impact on macroeconomic growth and price dynamics. This feedback loop ensures internal consistency between investment shocks and the broader economy. The process is continued until the divergence between successive iterations becomes negligible. In our case, after one round of feedback, the macroeconomic indicators—such as output, prices, and factor returns—stabilized with minimal variation, indicating convergence. As a result, further iterations were not required.

Table 2
Cumulative investment in US$ million (baseline and Policy Scenario 2)

	Base run		Policy Scenario 2		Additional investment required	
Sector	2025–30	2025–50	2025–30	2025–50	2025–30	2025–50
Agriculture	241	626	241	626	0	0
Biofuel	66	154	63	129	–3	–25
Buildings	1131	4733	1131	4733	0	0
Cooking (rural)	87	230	87	230	0	0
Cooking(U)	502	1855	502	1855	0	0
Domestic (resource)	753	5079	568	3551	–185	–1528
Electricity	1290	12110	1958	26152	0	0
Gas	7	38	7	33	0	–5
Industry	188	3075	130	1223	–58	–1852
Transport (freight)	11489	53638	11033	48842	–456	–4796
Transport (passenger)	31852	166834	28835	143291	–3017	–23543
Biogas	5	40	5	35	0	–5
Green hydrogen	22	58	0	54	–22	–4
Total	48301 *(3.6% of cumulative SDP)*	262512 *(0.8% of cumulative SDP)*	44560 *(3% of cumulative SDP)*	230754 *(0.36% of cumulative SDP)*	–3741	–31758

5. Concluding Remarks

As India progresses toward its net-zero emissions goal by 2070, individual states are also initiating steps to align with this national target. Kerala's per capita emissions remain notably lower than the national average, largely due to its service-driven economy and limited industrial base. However, a significant share, 76%, of Kerala's electricity is sourced from other states. As these states undertake their own energy transitions, Kerala's dependence on imported power could pose risks to energy availability and price stability. Therefore, the state must increasingly rely on its own renewable energy resources and adopt energy-saving technologies across all sectors to ensure both energy security and a reduced carbon footprint.

A shift to a low-carbon economy entails adopting technologies that often require substantial capital outlays. Assessing the economic viability of such transitions becomes essential. This study uses an integrated modeling strategy, linking a CGE model with a bottom-up energy model (MESSAGEix), to evaluate the economic, environmental, and employment outcomes of various policy pathways. The dynamic model simulates Kerala's transition across short-, medium-, and long-term horizons, incorporating government policy targets and sectoral trajectories.

Findings suggest that curtailing fossil electricity imports without expanding renewable energy infrastructure could constrain growth. In contrast, investing in local renewable capacity, coupled with improvements in energy efficiency and productivity, can generate positive economic returns, boost factor incomes, and create employment opportunities. However, such transformation requires active policy support. Kerala cannot rely indefinitely on electricity imports, especially if other states encounter hurdles in their clean energy transitions. To ensure a stable and sustainable pathway, the state must prioritize scaling up renewables, reducing energy intensity, and designing policy incentives that encourage green investments.

Our study shows that by imposing an import ban on fossil-fuel-based electricity while improving energy efficiency and productivity, Kerala can pursue a green transition and reduce emissions without compromising GDP growth, consumption, returns to labor and capital, or other key macroeconomic indicators. Despite the promising outlook, Kerala faces several obstacles in realizing its green transition. These include inadequate financing mechanisms, regulatory uncertainty, technological constraints, and social acceptance issues. Kerala's expenditure on the renewable energy sector accounts for about 0.1% of the total state budget and 0.22% of the state's total energy budget, based on the 2022–23 actual budget estimates. Given the limited scale of public spending, private sector participation is therefore critical for expanding renewable energy deployment. Mobilizing funds through instruments like green bonds, climate finance, and public–private partnerships, along with clear policy guidelines and regulatory support, will be vital [45]. Moreover, public engagement and ensuring equity in energy transition are essential for achieving a just and inclusive shift.

Enhancing energy efficiency and labor productivity are complementary strategies. Energy efficiency is currently limited by technological gaps, financial barriers, and weak regulatory incentives. Solutions include investing in efficient equipment, smart grid technologies, low-emission transport systems, and modern energy infrastructure. Productivity gains require skills development, innovation-friendly policies, and entrepreneurial support. The state can play a catalytic role by improving infrastructure, streamlining regulations, and funding R&D.

Kerala's low-carbon transition requires a coherent policy framework that prioritizes energy security, investment mobilization, and inclusive growth. First, the state must accelerate the expansion of domestic renewable energy capacity, particularly rooftop solar, decentralized systems, and small hydro, to reduce its heavy dependence on imported electricity. This should be complemented by investments in energy storage and grid modernization to ensure reliability. Second, given the limited scale of public expenditure, Kerala needs to strengthen financing mechanisms by leveraging green bonds, blended finance, and public–private partnerships, alongside establishing a dedicated green finance facility to crowd in private capital. Third, enhancing regulatory certainty through stable tariffs, clear renewable purchase obligations, and streamlined approval processes is essential to attract investment. At the same time, an aggressive energy efficiency strategy, covering buildings, industry, and transport, can reduce energy intensity and lower costs. Skill development and innovation policies must also be integrated to improve labor productivity and support emerging green sectors. Importantly, the transition must remain just and inclusive, with safeguards for vulnerable consumers and support for community-based energy initiatives. Finally, a flexible and adaptive policy approach is needed to respond to evolving technological and market conditions, ensuring a sustainable and growth-enhancing transition pathway.

While the CGE model assumes perfect market conditions, which may not reflect all real-world complexities, it provides directional insights into how macroeconomic indicators may evolve. In a standard CGE framework such as the GTAP model, the assumption of perfect markets implies that prices are fully flexible and adjust to clear all markets, ensuring full employment of labor and capital. As a result, policy shocks are absorbed through price changes and resource reallocation across sectors rather than through unemployment or idle capacity. Firms operate under zero-profit conditions and price equals marginal cost, which rules out market power and economic rents. While this provides a useful long-run equilibrium benchmark, it may overstate the efficiency and speed of adjustment, as it does not consider frictions like wage rigidities, capital adjustment costs, and financing constraints, which can lead to transitional unemployment and slower structural change. So, the effect of these frictions cannot be addressed through the CGE model and can be considered a limitation of it.

A carbon tax is generally not considered a short-run policy instrument in India due to political and economic constraints. Policymakers prioritize growth, affordability, and energy access, making direct carbon pricing difficult to implement quickly. Instead, India relies on indirect mechanisms such as the coal cess and schemes like the Perform, Achieve and Trade Scheme. For these reasons, a carbon tax scenario is not considered in our CGE model; however, it is discussed in the literature section, as our analysis involves taxing the fossil fuel sector and recycling the revenue to support the development of the renewable energy sector. This is also consistent with recent policy discussions, as carbon taxation is not treated as a short-run policy instrument in NITI Aayog's reports on Scenarios Towards Viksit Bharat and Net Zero (2026) [46].

The calibration process imposes hard constraints by forcing the model to exactly reproduce base-year economic and technological structures, limiting its ability to generate endogenous structural change. It also introduces a bias of the past, as future outcomes are anchored to historical patterns, often underestimating the diffusion of new technologies and transformative transitions. Overall, the study concludes that with the right mix of policy interventions, Kerala's low-carbon energy transition could become a growth-enhancing, employment-generating, and self-reliant development strategy. Selecting an appropriate policy framework that aligns with the state's socio-economic context will be key to achieving these goals.

Acknowledgment

The authors would like to acknowledge Ms. Sadhna Singh for her logistical and editing support throughout the preparation of this manuscript.

Ethical Statement

This study does not contain any studies with human or animal subjects performed by any of the authors.

Conflicts of Interest

The authors declare that they have no conflicts of interest to this work.

Data Availability Statement

Data are available from the corresponding author upon reasonable request.

Author Contribution Statement

Sanjib Pohit: Conceptualization, Writing – original draft, Writing – review & editing, Supervision, Project administration. **Chetana Chaudhuri:** Conceptualization, Validation, Formal analysis, Investigation, Resources, Writing – original draft, Writing – review & editing. **Anindya Bhattacharya:** Conceptualization, Writing – original draft, Writing – review & editing, Supervision, Project administration. **Somya Mathur:** Methodology, Software, Visualization. **P L Beena:** Conceptualization, Supervision. **Devender Pratap:** Methodology, Software, Data curation. **Mohit Kumar Meena:** Methodology, Software, Visualization. **Hrushikesh Mallik:** Resources. **Ritika Jain:** Resources. **Malavika Thampi:** Data curation.

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How to Cite: Pohit, S., Chaudhuri, C., Bhattacharya, A., Mathur, S., Beena, P. L., Pratap, D., …, & Thampi, M. (2026). Pathways to a Green Transition in Kerala: Economic and Employment Impacts from a State-Level Integrated Assessment. *Green and Low-Carbon Economy*. https://doi.org/10.47852/bonviewGLCE62026965