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# Dynamics of Energy Consumption, Economic Growth and Carbon Emission in a Sub-national Economy Context of India: An Evidence from Kerala

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**Abstract:** On examining the relationship of energy consumption with economic growth and carbon emission, we provide the evidence that the petroleum consumption growth significantly contributes to GSDP growth of Kerala (as indicated from regression coefficient of 0.70%), whereas electricity consumption growth affects GSDP growth with a time lag (as evidenced from Granger causality and regression coefficient of .13%). In contrast, GSDP growth of the state drives up both electricity and petroleum consumption demand, along with an observed strong elasticity of substitution relationship between consumption of two energy components (coefficients varying from 30% to 66%). We further find that the growth of transportation sector activities measured from transportation output which significantly contributes to gross emissions (as reflected from regression coefficient of .32%) rather than the overall GSDP growth of the state, suggesting that the demand for petroleum product increases with increased income growth without regard for its environmental concerns over the long-run. This is occurring more especially when amounts of $CO_2$ emission are very much lesser in the state as compared to the national average of all the states in India.

**Keywords:** energy consumption, $CO_2$ emissions, economic growth, climate and environment, Kerala, India

## 1. Introduction

Given the severe uncertainties engulfing climate change experiences as observed from the disturbances in natural water cycle around the world, certain regions have frequently been witnessing more intense rainfall and consequential heavy flood situations, while others experience severe drought conditions. The Intergovernmental Panel on Climate Change [1], Walker et al. [2], Nehemy et al. [3], and Ren et al. [4] explain the climate vulnerabilities arising due to carbon emissions and water cycles. In absence of any sub-national studies in India, especially on Kerala, this study investigates the association between energy consumption and economic growth and its consequences on carbon emission and climate change implications. It relates them with an aim to establish if some statistical relationships can be uncovered between them towards formulating environmental and climate policies given that there are major debates surrounding Environmental Kuznets Curve (EKC) hypothesis, suggesting higher is level of economic development, lesser is emission level [5]. Underlying this hypothesis, empirical investigations are proliferated to validate it for countries, regions and continents. Kerala being one of the highest achievers in human capital development in India based on its unique development experience (Kerala Development Model) distinguishes it from other states in India. Thus, it is imperative to scrutinize the issue of energy consumption and its implication for environmental and climate sustainability goals in light of recent vulnerability exposures of Kerala to massive flood and landslides in recent years since the year 2018. The study focuses on to investigate whether increased income of the state leads to significant energy demand mainly from two conventional sources viz. electricity and petroleum products or vice-versa in line with prediction of EKC hypothesis, where people moderate their energy demand as their incomes improve.[1] Based on our empirical findings, one can imply for policy whether increased energy consumption in the state is associated with greater carbon emissions, which has implications for climate change and natural vulnerabilities of the state such as land slide and flood experience as witnessed in 2018 and in subsequent years including the most recent Waynard experience in 2024[2], leading to displacement of people, loss of lives, properties and affecting major economic activities viz. agriculture, tourism etc.[3] We

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[1] In 2021–22, SGDP per capita at constant prices in 2011–12 base is Rs. 162,752, which is higher than the national average of Rs. 115,745.86. Covid-19 had affected economic activities of the state during 2019-20. Per capita income grew at −8.95% and GSDP at constant prices grew at -8.50% in 2020–21 over 2019–20. Given the data limitations associated with the study, our goal here is not to test EKC hypothesis than relate the variables of our interest.

[2] On 30 July 2024, a heavy rainfall triggered devastating landslides in Wayanad, Kerala. This wiped out two villages reflecting the consequences of climate change affecting an estimated total of 5000 people (loss of life amounting to 392 people, with 150 people reported missing and 273 injured) and suggesting the need for a robust adaptation strategy.

[3] It undertakes a partial observation on the relationship among variables as it does not consider cross externalities associated with Kerala's energy consumption on its neighbouring states and vice-versa.

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also try to observe whether there exists any substitutability relationship between consumption of two energy components despite constraints on availability of long-term data on renewable energy demand including information on non-renewable energy demand, although some renewable energies (minor fraction of total energy) are embodied in the production of electricity and that might have substitution implication for consumption of petroleum and other energy sources.

It is noted that nearly 70% of Kerala's total power imported from neighbouring states, is mostly coal-based power. Although this pattern of energy reliance keeps $CO_2$ emission under check within the state, but the import of it releases emissions into other neighboring states including source states. Kerala is most likely to face shortage of cheap power supply when all its neighbouring states implement the nationally determined targeted low carbon or net zero carbon pathway by 2070 similar to Kerala and all other states in India. Thus, Kerala needs to explore its potential of tapping or extracting energy from alternative non-fossil fuel sources, if other states fail to provide regular energy supplies during this transition period. The state may need to explore new alternative renewable energy sources like waste to energy, offshore wind farm, floating solar firms on water bodies etc. These will reduce its reliance on fossil fuels while continuing with high growth or without compromising its future potential growth.

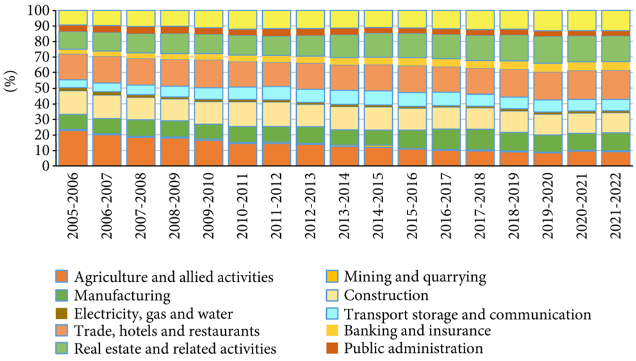
The relationship between economic growth, energy consumption, and $CO_2$ emissions at the state level in India is a crucial area of research due to India's federal structure and varying developmental patterns across states. The literature primarily explores how economic expansion influences energy demand and emission levels while assessing strategies to achieve sustainability goals [6, 7]. Before we statistically unearth the relationships among variables, we at first examine sector-wise output growth performance and put major emphasis on the energy intensive sectors like transportation, and real estate, housing and dwelling, trade, hotel and restaurant, and other sub-sectors of manufacturing and services along with examining the performance of broad-based sectors. We also examine output shares of various sectors in relation to GSDP and then we take a look at sector-wise demand for electricity and petroleum products and similarly we take a look at the sector-wise releases of carbon emissions as to establish whether growth of energy intensive sectors is leading to increased growth of $CO_2$ emissions in the state.

Keeping millennium sustainable development goals in mind, this piece of research investigates how consumption of two most crucial energy components from conventional sources and their resultant carbon emissions are aiding in or depressing economic growth of the state. Besides, it investigates which of the components of conventional energy is resulting in greater emissions and given the sustainable development goals of India and the state economy, whether there is any kind of substitution relationship between two energy components. These dynamics are not empirically probed for any state specific context in India which the study explores. Before we empirically investigate these issues, the study analyzes the growth performance of various sectors in the state as to provide some intuition whether most growing sectors are more energy intensive or less energy intensive. If more energy intensive, then given their implication on climate change, policy needs to be strategized to reduce their effect on climate change without offsetting their growth rates.

## 2. Sectoral Output Shares in Kerala

Figure 1 reports that amongst three broad output sectors, service sector has the highest share followed by industry and agriculture. By further examining the sub-sectors, Trade, Hotels and Restaurants shows the highest output share followed by Real Estate, Ownership of Dwellings and Business Services output, construction output, other services, manufacturing and agriculture.

**Figure 1**
**Sectoral output shares in Kerala (%)**



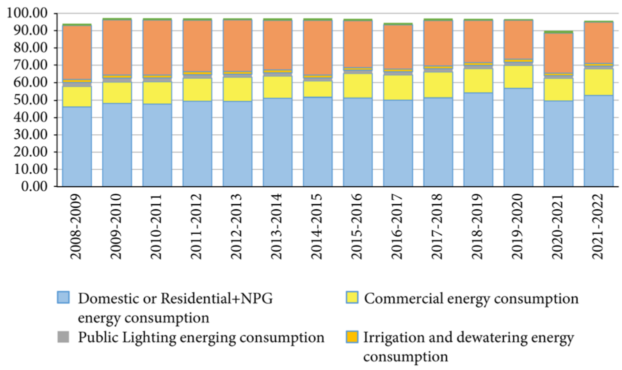

## 3. Sectoral Energy Consumption Shares of Various Sectors (Electricity and Petroleum) in Kerala

In the absence of energy statistics from various sources, we examine energy consumption from two broad sources, electricity and petroleum products. In the absence of strong and vibrant manufacturing sector in Kerala, Figure 2 indicates that it is the domestic sector which consumes highest share of electricity energy followed by its industrial and commercial sectors in Kerala. The state government statistical reports suggests that Kerala meets its substantial portion of energy demand by purchasing power from other states. Power generation in Kerala is 10,888.01 MU in 2021–22, while energy sale is reported as 24,991.46 MU during the same period. As per KSEB statistics (2021–22), the net of external loss and of auxiliary consumption, total generation of power in Kerala was 9763.05 million units, while total Power Purchase at delivery point is 18,887.67 million units (KSEB 2022[4]). Thus, 66% of total generation and power purchased by KSEB is purchased at the delivery point, i.e. not generated within the state. This might be one of the leading reasons which might be contributing to low emission in the state. Further, the major source of power generation in Kerala is hydro (85%), followed by small hydro (8%), solar (4%), wind (2%) and oil and gas (1%). Given a negligible or minimal extent of reliance on thermal power is also contributing to less emission from power sector.

## 4. Share of Electricity Generation in Kerala

Figure 3 shows that there is less reliance on gas and petroleum products in generation of electricity in the state. Electricity generation within Kerala is mainly hydro based which is the major source of

**Figure 2**
**Electricity consumption shares in Kerala (%)**




[4] Kerala State Electricity Board Limited: https://kseb.in/ksebdashboard.

**Figure 3**
**Sources of electricity generation in Kerala**

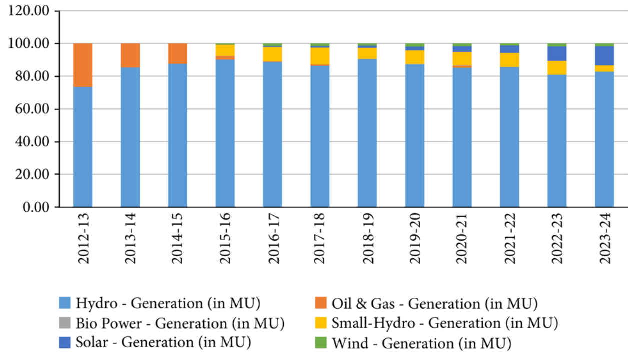
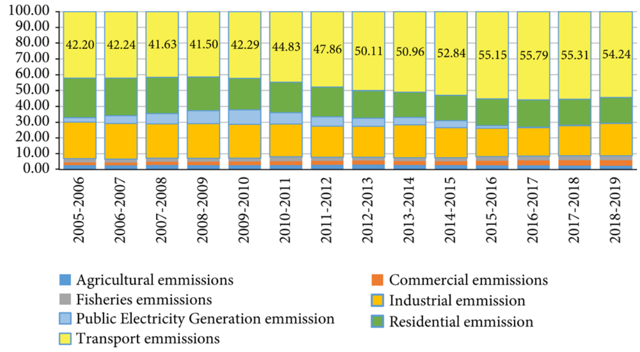



**Figure 5**
**Emission shares in Kerala (%)**



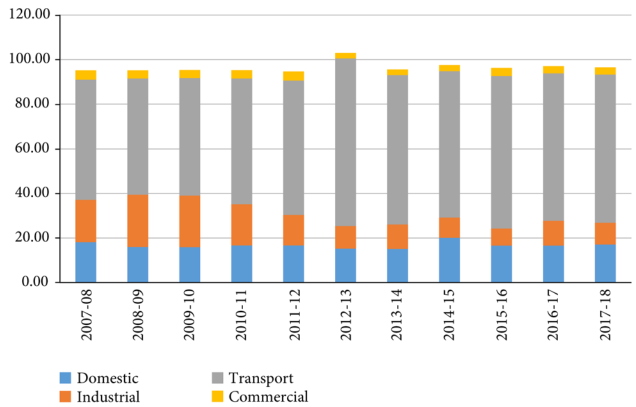

power generation. This is one of the key factors which contributes to low emissions in the state besides a weak industrial sector. However, in the course of importing electricity from neighbourhood states to fulfil its own energy demand, how much carbon emission the neighbouring states absorb and how much they emit into Kerala along with other externalities from their overall carbon emissions leading to Kerala's climate change is beyond the scope of the present study due to inherent statistical complexities and data unavailability. Rather, we look into the trends of carbon emission generated within the state. It is also imperative from policy to understand climate change in Kerala and how much to attribute to external and internal emissions of Kerala.

Figure 4 shows sectoral share of petroleum product consumption. It shows transportation sector has the dominant share (66%) of petroleum consumption followed by domestic (17%) and industrial sectors (10%) as on 2017–18.

## 5. Sector-wise Emissions in Kerala

As per the data provided by GHG platform India (a civil society analyzing India's greenhouse gas emissions comprising of Council on Energy, Environment and Water (CEEW), The International Maize and Wheat Improvement Center (CIMMYT), Center for Study of Science, Technology and Policy (CSTEP), ICLEI - Local Governments for Sustainability, and Vasudha Foundation) shows, the net emission in Kerala is 1.21 Mt $CO_{2e}$ in 2021, which is 0.04% of India's gross emissions. Per capita emission level of 0.09 t $CO_{2e}$ is also quite low in Kerala as compared to the national average (2.24 t $CO_{2e}$ per capita). Examining the share of emission from various sources, Figure 5 shows that it is the transportation sector which significantly contributes to $CO_2$ emission followed by industry and residential sectors. Electricity generation contributes least as most power plants are hydrogen based in Kerala.

**Figure 4**
**Sectoral shares of petroleum product consumption**

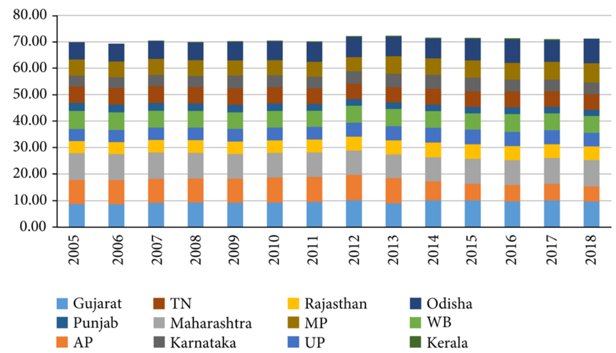



## 6. Relative Contributions of Kerala to Gross $CO_2$ Emissions vis-a-vis Selected Indian States

When we compare relative $CO_2$ emissions across Indian states, we observe from Figure 6 Kerala's contribution to gross national emission is barely less than half a percentage. This is negligible comparing states like Maharashtra (9.82%), Gujrat (9.72%) and Odisha (9.30%) which have maximum percentage of contributions to gross national emissions.

Given Kerala's meager emission compared to national average, when the planetary system is already burdened with substantial accumulated carbon gases, any marginal addition to the existing accumulated emission by any small region can add further woes to global warming and climate change including its effects on various regions and sub-regions. In such context, it is important to relate energy demand of Kerala and its contributions to state's income or output growth, and environmental cost and quality emanating from carbon emissions in Kerala, where human quality index stands out at a higher level among the Indian states with higher percentage of literates among its populace, along with good health performance indicators. Although the state has successfully and consciously controlled the growth of its population (Figure A1) but its density is relatively high in India because of its smaller geography. This is also accompanied by higher urbanisation which can impact the environmental quality and higher population density and quality of human capital. Although sustainable growth remains a global priority under the Millennium Development Goals, several studies from both India and international contexts have examined the potential trade-off between energy consumption and economic growth, suggesting that efforts to reduce energy use may improve environmental quality but also risk lowering

**Figure 6**
**Relative carbon emissions across Indian states**



economic output [8–10]. For example, Ediger and Huvaz [8] found that in Turkey, energy consumption is a key driver of future GDP, and that declining energy use, if following historical trends, could lead to slower economic growth. Similarly, Gross [9] observed that even in the absence of long-run causality at the aggregate level, energy-reduction policies can significantly impact individual sectors in both the short and long term. In such studies, while authors have examined the role of increased population, educational attainment and urbanisation which exert pressure on environment or bio-capacity, however, these features remain unaddressed in a small sub-regional context of Kerala, owing to lack of statistical data. Given data constraints on energy consumption and $CO_2$ emission on a historical basis for sub-regions, the study examines the role of energy consumption on economic growth and their implication on carbon emission by considering a shorter time period for which the data is available from authentic sources. Based on empirical observation, we try to imply for policy at a sub-regional context. In the absence of literature at the sub-regional level, we summarise few important studies at the international levels presenting the dynamics of energy consumption demand, carbon emission and economic growth.

## 7. Literature Survey

### 7.1 Energy consumption and economic growth

Numerous studies have investigated the relationship between energy use and economic growth and their implication on environmental pollution for individual and panel of countries. Shahbaz et al. [11] while addressing the question of does globalisation moderate energy demand through adoption of foreign technologies and knowledge transfers for India, also examined whether financial development, urbanisation and economic growth determine energy demand. They observed a robust positive association between the two along with increased urbanization, suggesting that economic growth Granger causes energy demand and vice-versa. They implied that in short-run, an energy policy that discourages energy demand may compromise economic growth. Observing an adverse impact of globalization on energy demand, they suggested that it is vital for the government to design policies and undertake strategies to address backlash of globalisation while opening up the economy for enhancing international trade and attracting more foreign capital. Considering world bank database for 152 countries, Perera et al. [12] observed a uni-directional causality both from renewable energy consumption and non-renewable energy consumption to economic growth in transitional economies. Given the interconnectedness, they suggested that the policymakers should focus on both variables while making decisions. Implementing global energy efficiency standards, reducing fossil fuel usage, and adopting regulatory measures are all viable policies for limiting adverse effects on environment while encouraging economic development. Hao and Deng [13] demonstrated total index of energy consumption structure in China is relatively low and the regional economic development mainly depends on low-grade energy. Sadraoui et al. [14] showed energy consumption has a high positive impact on growth. Mohsin et al. [15] examined the relationship between economic growth and energy consumption. They showed that economic growth driven at the cost of energy consumption leads to urban environmental degradation, is a deviation from sustainable development path targets. Most studies carried out at the country levels they establish the dynamics of other factors like financial development, international trade (exports and imports) or openness or globalisation measures to energy and economic growth relationship, but the statistics on the same indicators are largely missing at a sub-national level to uncover their dynamics. Therefore, our study is unable to consider the role of international and domestic macro factors while attempting to explore energy consumption and growth relationships at the sub-national level.

### 7.2 Energy consumption and carbon emission

By initiating the debate on EKC, Grossman and Krueger [16] explained the relation between environmental pollution and economic growth through an inverted U-shape curve. As regard to the environmental consequences of international trade, they argued that environmental effect of international trade hinges on regulation and implementation of energy policies of an economy. In this connection, two contrasting schools of thought became prominent on the impact of international trade on $CO_2$ emissions. The first school of thought postulated trade openness provides an opportunity for each and every country to access benefits of international trade, which in turn, enhances market share of participating countries in international trade. The second strand viewed that natural resources are depleted on account of increasing participation of countries in international trade. These depletions raise $CO_2$ emissions and cause environmental degradation [17–19].

Using input–output analysis, Dietzenbacher and Mukhopadhyay [20] investigated whether India is a pollution haven. They observed that India considerably gained from extra trade as it had moved further away from being a pollution haven. Ghosh [21] investigated the long-run associations between $CO_2$ and economic growth along with incorporating investment, employment, energy supply in India. Observing an absence of long-run causality between $CO_2$ emission and economic growth, they implied that the long-run focus should be to harness energy from cleaner sources to curb carbon emissions, which wouldn't affect country's potential growth. However, observing a two-way causality between $CO_2$ and growth in short-run, they implied that any effort to reduce carbon emissions would compromise with its national income. The absence of causality from energy supply to growth implies that energy conservation and energy efficiency measures can minimize energy wastage across value chain, which would narrow energy demand-supply gap. Chandran and Tang observed a no long-run relationship between carbon emission, economic growth and coal consumption while they detected a short-run causality between growth and $CO_2$ emissions and $CO_2$ emissions and coal consumption besides a uni-directional Granger causality from growth to coal consumption in India. However, they observed a long-run relationship among these variables for China, suggesting a strong uni-directional causality from growth to $CO_2$ emissions and a bi-directional causality between growth and coal consumption and $CO_2$ emissions and coal consumption in short and long-run for China. However, to account for a regime change, Kanjilal and Ghosh [22] used the threshold cointegration model to reinvestigate the relationship between $CO_2$ emission, economic growth, energy use and trade openness for India. Their finding of a 'regime-shift' or 'threshold' cointegration and EKC for India challenged the earlier results of no long-run relationship and absence of EKC hypothesis for India. They found high elasticity of carbon emission with respect to real per capita income and use of energy in India.

Goswami et al. [23] assessed the impact of economic growth, trade openness, urbanization, and energy consumption on carbon emissions in India; (2) Methodology: In this longitudinal study, data have been collected from World Development Indicators and Our World in Data from 1980 to 2021. The finding revealed that in the long run, energy consumption, urbanization, and trade openness are positively correlated with $CO_2$ emissions, while economic growth and $CO_2$ emissions at previous lag demonstrated a negative correlation. Kundu and Chakraborty [24] examined the effect of GDP, rate of urbanization (UR), structure of trade (TS), proportion of coal consumption (CS), and Shannon -Wiener Index (SWI) reflecting the structure of energy consumption on $CO_2$ emissions in India over 1990–2021. It observed that Environmental Kuznets Curve hypothesis does not hold good for India and an increase in SWI reduces carbon emissions; and a diversified trade structure negatively affects the growth of carbon emissions. Parikh and Dhananjayan [25] examine the relationship between $CO_2$ emissions and economic growth at the state level in India. They find that while industrialized states contribute more to emissions, they also have higher energy efficiency initiatives. They also suggest that less developed states may require financial and policy support to integrate clean energy technologies without hindering their economic growth. The study emphasizes that achieving India's net-zero carbon targets requires a state-specific approach rather than a one-size-fits-all policy. By recognizing regional economic and energy disparities, policymakers can design tailored strategies to promote renewable energy, reduce emissions, and sustain economic growth.

Zhang et al. [26] discussed how economic growth pressure impacts carbon emissions across 277 cities in China. They find that economic growth pressure significantly infuses carbon emissions through reducing technological innovation and foreign trade, and the absence of mediating mechanism of industrial structure upgradation. Sarkodie and Strezov [27] established a strong positive impact of energy consumption on greenhouse gas emissions. Tran et al. [28] examined if human development, energy consumption and carbon dioxin emissions depend economic development in 90 countries. of the confirm better human development leads to reduction of carbon emissions in global sample countries including developing countries. However, carbon emissions and human development do not exhibit a significant relationship in developed countries. They report absence of causality between energy consumption and human development for the global sample and for the sub-panels. Ehigiamusoe and Lean [29] observed that high-income level and financial development reduce carbon emissions, while low-income and financial development aggravates it in China. This finding is similar to their earlier finding where they found energy consumption, financial development and growth worsened carbon emissions for a sample of 122 countries. On splitting sample into different income groups, it revealed that financial development and growth alleviate carbon emissions in high-income countries but had the opposite effect in low and middle-income group countries. The findings implied that energy consumption causes carbon emissions. While high income level and financial development curb emissions, financial development and low income aggravate it.

There are some studies at the country level or at the subnational levels of other countries. For instance, Altin [30] analyzes the impact of energy efficiency and renewable energy use on carbon emissions in G7 countries and find a long-run cointegration relationship between energy efficiency, renewable energy use and carbon emissions. González-Álvarez and Montañés [31] studied the stability of the energy–economics–environment relationship and found $CO_2$-economic growth elasticities have reduced since the Great Recession, while $CO_2$-energy elasticities have increased since the Great Recession. Recent studies by Tang and Zhou [32], Sun and Chen [33], Gu et al. [34], Zhang et al. [35], Zhou et al. [36], Wang and Wang [37], Yang et al. [38], Chen and Chen [39], Huang and Chen [40], Huang et al. [41], Liu et al. [42], and Zhou and Tang [43] have analyzed the impact of green finance on the structure of energy consumption, and $CO_2$ reduction in various regions of China, which is not done for India.

In overall, while exploring the dynamics between economic growth and energy use, the studies mostly have incorporated the role and dynamics of trade and financial development on growth and energy consumption for various countries, similarly studies also have investigated the role of trade and financial development on emissions. But there are hardly similar studies available for the small sub-regional context. Moreover, while there are abundant studies analysing energy consumption and economic growth, while attention is not drawn on the same in a sub-regional context of India. In the absence of availability of historical official data over a long period on variables of our interest, the study makes a preliminary observation based on the regression and causality tests among the variables for Kerala. Thereby, our study contributes to improve our understanding on the relationship between energy consumption, growth and emissions at the sub-national level. Given the high spatial variation across states, each state's experience will offer policy lessons for the national level and for other states as well. Against this background, this piece of research investigates how consumption of two most crucial energy components from conventional energy sources and their resultant carbon emissions are associated with economic growth of Kerala. We also investigate which components of conventional energy consumption is giving rise to greater emissions and given the sustainable development goals of India and the state economy, whether there is any kind of substitution relationship between two energy components. These dynamics are not empirically investigated for any states or regions in India which we explore.

Before we empirically investigate these issues, we analyze growth performance of various sectors in the state as to provide some intuition whether most growing sectors are more energy intensive or less energy intensive. If more energy intensive, then given their implication on climate change, policy needs to be strategized to reduce their effect on climate change without offsetting their growth rates. To set the background of our analysis, although we tried to examine the growth performance of broad sectors and sub-sectors in relation to energy consumption demand in respective sectors but for an empirical analysis, we are primarily concerned about discovering the linkage between overall real growth of state income and growth of petroleum and electricity energy consumption demand. This is mainly due to paucity of long-term data at the sub-sectoral level. Thus, we focus on uncovering the statistical relationships of growth rate of key variables for a sub-national economy of India, i.e. Kerala, besides analysing an energy intensive sector like transportation in the absence of such analysis in the literature.

## 8. Data Source

We cover a short span of time series data from 2005–06 to 2020–21. To measure total output or income of Kerala, we consider GSDP of Kerala at constant prices. The statistics on GSDP is drawn from EPW Research Foundation (EPWRF). The total and sectoral emission data are collected from GHG platform India database. It provides emission statistics for the country as a whole and state-wise.[5] Petroleum consumption data is compiled from a study report prepared by Pillai and Am [44] on "Energy Efficiency: A Sectoral Analysis for Kerala" at CDS & EMC and statistics on electricity consumption of Kerala is extracted from the report on Power System Statistics published by Kerela State Electricity Board (KSEB) Ltd. and this is also verified with the report produced by WWF and Wise. All the data are considered in real terms, wherever required real values are obtained by deflating with respect to GSDP deflator and then later transformed them into simple growth rates by taking difference of natural logarithmic values of their respective series.

## 9. Empirical Results Analysis

Table A1 reports that petroleum product is highly correlated with GSDP. The transport and storage output also exhibits strong correlation with total electricity consumption. The transport emission is correlated with electricity consumption and transport and storage output. And railway traction energy is correlated with transport and storage output and rest are not correlated with other components.

Since we consider growth rates of all variables, the application of conventional unit roots such as ADF and Phillips-Perron tests ensures stationarity in their levels. The results on unit root tests are compiled in

[5] Emission statistics is available in Trend Analysis of GHG Emissions of KERALA.

Table A2. The stationarity of growth rate variables also justifies that the OLS estimates would be consistent and robust. Table 3 clearly shows that it is petroleum consumption growth rate which drives the growth of GSDP not the electricity consumption growth rate in Kerala.

Table 4 shows that it is the growth of income augmented due to increased remittance receipts in the state, which might be associated with the overall demand of petroleum, as with increased income, people increase their demand for number of vehicles besides investing on land, housing, gold assets and incur health (medical expenses) and educational expenditures. However, it also reveals the possibility of a strong substitutability relationship between petroleum consumption and electricity consumption in the state as observed from both the regression results reported in Table 4. The substitution elasticity parameter varies from 30% to 66%. Thus, people might be switching their pattern of consumption demand between the above two energy sources. This also implies, when people become conscious of heavy atmospheric pollutions from petroleum and diesel driven vehicles, they might go for electric driven vehicles for saving the environment from pollution.

**Table 3**
**Regression of energy consumption on GSDP**

| | **Dependent Variable: GSDP** | **Dependent Variable: GSDP** |
|---|---|---|
| Explanatory Variables | | |
| TOTAL ELECTRICITY CONSUMPTION | 0.132 (0.89) | – |
| PETROLUEM PRODUCTS CONSUMPTION | 0.702 (7.07)* | 0.653 (7.88)* |
| Intercept | 2.604 (2.418)* | 3.421 (6.17)* |
| *R*-squared | 0.861 | 0.850 |
| Adjusted *R*-squared | 0.88 | 0.836 |

**Note:** * significance at 1* level. The values in the parentheses are t-statistics of parameter estimates. The above is estimated utilising the available data from 2006–07 to 20019–20.

**Table 4**
**Demand for petroleum and electricity consumption in Kerala**

| | **Dependent Variable:** PETROLUEM PRODUCTS CONSUMPTION | **Dependent Variable:** TOTAL ELECTRICITY CONSUMPTION |
|---|---|---|
| Explanatory Variables | | |
| TOTAL ELECTRICITY CONSUMPTION | −0.30 (−1.66)*** | |
| PETROLUEM PRODUCTS CONSUMPTION | | −0.66 (−1.61)*** |
| STATE DOMESTIC PRODUCT | 1.184 (7.07)* | 0.53 (0.91) |
| Intercept | −1.98 (−1.20) | 4.86 (2.16)** |
| *R*-squared | 0.882 | 0.262 |
| Adjusted *R*-squared | 0.858 | 0.148 |

**Note:** * significance at 1% level, ** significance at 5% level and *** significance at 10% level. The values in the parentheses are t-statistics of parameter estimates. The above estimated values are based on the available data from 2006–07 to 20019–20.

**Table 5**
**Role of transportation growth and energy consumption on grand emissions ($CO_2$)**

| | **Dependent Variable: Grand Emission** | |
|---|---|---|
| Explanatory Variables | | |
| PETROLUEM PRODUCTS CONSUMPTION | 0.14 (0.483) | 0.040 (0.091) |
| TOTAL ELECTRICITY CONSUMPTION | −0.281 (−1.21) | −0.038 (−0.14) |
| TRANSPORT STORAGE & CONSTRUCTION OUTPUT | 0.324 (2.40)** | – |
| Gross STATE DOMESTIC PRODUCT | – | 0.17 (0.28) |
| Intercept | 3.75 (2.12)** | 4.34 (1.34) |
| *R*-squared | 0.395 | 0.017 |
| Adjusted *R*-squared | 0.193 | −0.311 |

**Note:** The asterisk mark follows the same significance level as in Table 4. The estimated values are obtained utilising the available data from 2006–07 to 20019–20.

Since transport sector dominantly consumes a greater share of petroleum products, it is useful to see the role of transportation sector output growth along with two energy sources, which one among them is strongly associated with $CO_2$ emissions. Table 5 reveals the growth of transportation output is positively associated with emission growth. However, when we substitute transportation output growth with overall GSDP growth, it overshadows the importance of transportation sector on overall emission growth in Kerala. This prediction follows from the fact that transportation growth might not be solely capturing all the pollutions due to oil consumption but it might also lead to increased demand for other pollution related products and components, which might lead to greater carbon emission ($CO_2$).

## 10. Robustness of Empirical Findings

To test the robustness of our findings, we have run bi-variate causality analysis in Table 6. It shows that income growth causes the emission growth. With increased growth of income, people might be demanding a number of products whose production and consumption might be leading to greater carbon emissions. In conformity with regression result, it also suggests that overall petroleum product consumption growth does not cause emission growth.[6] Rather, it is the emission growth which Granger causes electricity consumption growth. The government and international environmental agencies along with high educational achievements of the state might have led greater awareness among the people about the present and future consequences of accumulated emissions in the atmosphere, which might have induced the demand for cleaner and renewable energy sources like electricity from hydro, wind and solar although it can be produced from

[6] The finding of petroleum product consumption growth does not Granger cause emission growth, does not automatically confirm to petroleum product consumption might not significantly lead to emission growth in Kerala. This study did not attempt to relate the level variables on account of non-stationarity nature of time series variables.

**Table 6**
**Pairwise Granger causality tests**

| Sample: 2006–07 to 2019–20, Computed with Lags: 1 & 2 | | | |
|---|---|---|---|
| **Null Hypothesis:** | **Obs** | **F-Statistic** | **Prob.** |
| GSDP does not Granger Cause GRAND TOTAL EMMISSIONS | 12 | 1.65 | 0.27 |
| GRAND TOTAL EMMISSIONS does not Granger Cause GSDP | 12 | 0.41 | 0.68 |
| PETROLEUM PRODUCTS CONSUMPTION DOES NOT GRANGER CAUSE GRAND TOTAL EMISSIONS | 12 | 2.85 | 0.13 |
| GRAND TOTAL EMISSIONS DOES NOT GRANGER CAUSE ETROLUEM PRODUCTS CONSUMPTION | 12 | 0.35 | 0.72 |
| TOTAL ELECTRICITY CONSUMPTION does not Granger Cause GRAND TOTAL EMMISSIONS | 12 | 1.72 | 0.26 |
| GRAND TOTAL EMMISSIONS does not Granger Cause TOTAL ELECTRICITY CONSUMPTION | 12 | 6.05 | 0.04 |
| TRANSPORT, STORAGE &COMMUNICATION does not Granger Cause GRAND TOTAL EMMISSIONS | 12 | 2.93 | 0.10 |
| GRAND TOTAL EMMISSIONS does not Granger Cause TRANSPORT, STORAGE & COMMUNICATION | 12 | 0.92 | 0.45 |
| TRANSPORT EMMISSIONS does not Granger Cause GRAND TOTAL EMMISSIONS | 12 | 0.33 | 0.58 |
| GRAND TOTAL EMMISSIONS does not Granger Cause TRANSPORT EMMISSIONS | 12 | 2.27 | 0.17 |
| RAILWAY TRACTION ENERGY does not Granger Cause GRAND TOTAL EMMISSIONS | 11 | 1.94 | 0.22 |
| GRAND TOTAL EMMISSIONS does not Granger Cause RAILWAY TRACTION ENERGY CONSUMPTION | 11 | 0.64 | 0.56 |
| PETROLUEM PRODUCTS CONSUMPTION does not Granger Cause GSDP | 12 | 2.26 | 0.16 |
| GSDP does not Granger Cause PETROLUEM PRODUCTS CONSUMPTION | 12 | 4.18 | 0.06 |
| TOTAL ELECTRICITY CONSUM does not Granger Cause GSDP | 12 | 4.78 | 0.05 |
| GSDP does not Granger Cause TOTAL ELECTRICITY CONSUMPTION | 12 | 0.32 | 0.58 |
| TRANSPORT EMMISSIONS does not Granger Cause GSDP | 12 | 0.86 | 0.38 |
| GSDP does not Granger Cause TRANSPORT EMMISSIONS | 12 | 0.27 | 0.62 |
| RAILWAY TRACTION ENERGY does not Granger Cause GSDP | 12 | 14.10 | 0.00 |
| GSDP does not Granger Cause RAILWAY TRACTION ENERGY CONSUMPTION | | 0.13 | 0.73 |
| TOTAL ELECTRICITY CONSUMPTION does not Granger Cause PETROLUEM PRODUCTS CONSUMPTION | 11 | 3.14 | 0.10 |
| PETROLUEM PRODUCTS CONSUMPTION does not Granger Cause TOTAL ELECTRICITY CONSUMMPTION | 11 | 0.29 | 0.60 |
| TRANSPORT, STORAGE &COMMUNICATION does not Granger Cause PETROLUEM PRODUCTS CONSUMPTION | 11 | 0.47 | 0.52 |
| PETROLUEM PRODUCTS CONSUMPTION does not Granger Cause TRANSPORT, STORAGE & COMMUNICATION OUTPUT | 11 | 3.48 | 0.10 |
| TRANSPORT EMMISSIONS does not Granger Cause PETROLUEM PRODUCTS CONSUMPTION | 11 | 5.38 | 0.05 |
| PETROLUEM PRODUCTS CONSUMPTION does not Granger Cause TRANSPORT EMMISSIONS | 11 | 0.86 | 0.38 |

**Table 6**
*(continued)*

| Sample: 2006–07 to 2019–20, Computed with Lags: 1 & 2 | | | |
|---|---|---|---|
| **Null Hypothesis:** | **Obs** | **F-Statistic** | **Prob.** |
| RAILWAY TRACTION ENERGY CONSUMPTION does not Granger Cause PETROLUEM PRODUCTS CONSUMPTION | 11 | 7.37 | 0.02 |
| PETROLUEM PRODUCTS CONSUMPTION does not Granger Cause RAILWAY TRACTION ENERGY CONSUMPTION | 11 | 1.11 | 0.31 |
| TRANSPORT STORAGE & COMMUNICATION does not Granger Cause TOTAL ELECTRICITY CONSUMPTION | 11 | 6.02 | 0.03 |
| TOTAL ELECTRICITY CONSUMMPTION does not Granger Cause TRANSPORT, STORAGE & COMMUNICATION | 11 | 2.78 | 0.10 |
| TRANSPORT EMMISSIONS does not Granger Cause TOTAL ELECTRICITY CONSUMMPTION | 11 | 1.01 | 0.42 |
| TOTAL ELECTRICITY CONSUMMPTION does not Granger Cause TRANSPORT EMMISSIONS | 11 | 3.36 | 0.10 |
| RAILWAY TRACTION ENERGY CONSUMPTION does not Granger Cause TOTAL ELECTRICITY CONSUMPTION | 12 | 1.90 | 0.20 |
| TOTAL ELECTRICITY CONSUMMPTION does not Granger Cause RAILWAY TRACTION ENERGY CONSUMPTION | 12 | 4.33 | 0.06 |
| TRANSPORT EMMISSIONS does not Granger Cause TRANSPORT, STORAGE & COMMUNICATION | 12 | 0.20 | 0.82 |
| TRANSPORT STORAGE & COMMUNICATION does not Granger Cause TRANSPORT EMMISSIONS | 12 | 4.71 | 0.06 |
| RAILWAY TRACTION ENERGY CONSUMPTION does not Granger Cause TRANSPORT, STORAGE & COMMUNICATION | 12 | 3.95 | 0.06 |
| TRANSPORT STORAGE &COMMUNICATION does not Granger Cause RAILWAY TRACTION ENERGY CONSUMPTION | 12 | 3.13 | 0.09 |
| RAILWAY TRACTION ENERGY CONSUMPTION does not Granger Cause TRANSPORT EMMISSIONS | 12 | 3.41 | 0.10 |
| TRANSPORT EMMISSIONS does not Granger Cause RAILWAY TRACTION ENERGY CONSUMPTION | 12 | 0.98 | 0.43 |

**Note:** Granger causality is executed for pair of variables presented in consecutive two rows with the null hypothesis that there is no causality from one variable to the other.

thermal sources involving fossil fuel usage which is likely to generate more carbon emissions. However, there are no thermal electricity plants in Kerala. Rather the deficiency in electricity generation is being addressed by import of energy from neighbouring states like Tamil Nadu and Karnataka. Moreover, the two-way Granger causality might not be capturing the proper dynamics between variables in case absence of a third factor in the model is the cause of their real relationship.

It is noticed that the transport and storage output growth Granger causes emission growth which is similar to the earlier regression result. However, while our raw data hints that the transportation sector dominantly contributes highest to the grand emission, our Granger causality surprisingly reveals transportation sector does not significantly add to the grand emission growth. This could be because Kerala is one of the less emitters of carbon gases comparing the national average emissions of all states in India. The Granger causality similar to our previous regression estimation also suggests that growth of state income does not lead to growth of grand emission.

The growth of GSDP Granger causes growth of petroleum product consumption demand rather than the other way round. The latter result contradicts our previous regression result as there existed a two-way association between the both as indicated from regression results. Further, Granger causality reveals that electricity consumption growth causes income growth of the state which contradicts our regression result which indicated no relationship between electricity consumption growth and GSDP growth rate.

It also shows electricity consumption demand growth causes petroleum product consumption growth but petroleum product consumption growth does not cause the former. The former result supports our preceding regression result while the latter does not confirm it, while the regression estimates revealed substitutability relationship in both the directions. This to some extent partially indicates the substitutability relationship between the both energy consumption demand from two conventional sources.

It is the emission growth from transportation sector which leads to petroleum consumption growth but not the vice-versa. This is surprising. This may be due to the fact that emission growth from transportation sector hurts petroleum consumption and thereby might have indirect effect on electricity consumption demand. Our result shows the growth of emission from transportation Granger causes electricity consumption demand, while electricity does not lead to emissions from transportation in a significant way. This is in line with our expectation. Railway traction Granger causes petroleum product consumption but petroleum consumption does not Granger cause railway traction. This result could be due to dependence of electricity generation on petroleum products. The growth of transport, storage and communication Granger causes growth of electricity consumption demand and growth of electricity consumption demand Granger causes growth of transportation, storage and communication activities (output). The growth of railway traction energy consumption Granger causes growth of transportation, storage and communication, while transportation, storage and communication activities have also some weak causality relationship with the former. The growth and increase of transport and storage, communication activities Granger causes transportation emission but vice-versa not holding true. Most of our causality results are along our regression results except some minor aberrations. Most causality results are also found to be robust even we test causality with lag 2. Although there are minor deviations in our Granger causality test results from regression results, however, the differences could be due to the differences in methods. The regression results do not account for time dynamics, while Granger causality incorporates time dynamics in the estimation through its lagged impact.

## 11. Forecasted Energy Demand for Kerala

We have tried to forecast the GSDP growth rate, transportation and storage output growth rate, petroleum and electricity consumption demand and emission growth rates to understand their time path and directions of these indicators in another eight years, given the aim of the state government for attaining zero net emissions by 2070. This would give insight for policy formulation - how the state is ready in terms of achieving its objective. Although several variables might play important dynamism in shaping the growth of energy demand, economic growth rate and therefore the carbon emission, in the absence of long time series of these variables, it is impossible for us to take into account of those factors for generating forecast for next eight to 15 years. We have projected the growth rate of key variables based on ARIMA modelling technique, where our ARIMA model involves using a maximum lag of 2 for both AR and MA terms on the stationary series (growth rate series). Even the actual values of GSDP and transportation and storage output growth rates, energy demand growth rates are available for 2020–2021 except emission growth rate but we did not use the actual values of variables for 2020–21 to simulate the energy consumption demand due to severe fluctuation in values of variables on that year. Rather, we have generated the forecasted values of all variables from 2020 onwards as the year 2020–21 is considered non-normal on account of COVID-19 seriously affecting the trends of all economy series of India and the entire world. Therefore, treat 2020–21 as a normal year like before, for a proper forecast, we have projected values based on previous normal years by dropping the actual values of 2020–21. Our model generates the forecasted values of variables since 2020–21 as reported in Table 7.

**Table 7**
**Projected growth rates of GSDP, transportation and storage output and other energy components for Kerala**

| | GSDP F | Transport and storage output F | Petroleum Product F | Total Electricity F | Grand Total Emission F |
|---|---|---|---|---|---|
| 2006 | 7.60 | 14.60 | | 9.83 | |
| 2007 | 8.41 | 13.71 | | 6.15 | 7.52 |
| 2008 | 5.41 | 15.44 | | 6.64 | 6.41 |
| 2009 | 8.77 | 16.55 | 7.80 | 6.04 | 9.59 |
| 2010 | 6.69 | 13.27 | 1.58 | 8.07 | 8.40 |
| 2011 | 5.69 | 12.38 | 0.52 | 12.70 | 3.84 |
| 2012 | 6.29 | 5.01 | 6.86 | 9.02 | 2.40 |
| 2013 | 3.82 | 10.15 | 0.08 | 0.57 | 4.69 |
| 2014 | 4.18 | 4.26 | 1.84 | 5.98 | 8.07 |
| 2015 | 7.18 | 3.56 | 2.95 | 4.39 | 2.21 |
| 2016 | 7.28 | 4.09 | 3.06 | 5.69 | 0.20 |
| 2017 | 6.17 | -4.78 | 7.09 | 1.26 | 3.55 |
| 2018 | 7.11 | 3.32 | 3.11 | 0.84 | 7.38 |
| 2019 | 2.19 | 4.93 | 3.02 | 0.84 | 5.08 |
| 2020F | 6.16 | 6.07 | 2.38 | 3.55 | 5.29 |
| 2021F | 6.20 | 6.86 | 3.02 | 4.85 | 5.37 |
| 2022F | 6.20 | 7.41 | 3.17 | 5.32 | 5.39 |
| 2023F | 6.20 | 7.80 | 3.20 | 5.48 | 5.40 |
| 2024F | 6.20 | 8.06 | 3.21 | 5.54 | 5.40 |
| 2025F | 6.20 | 8.25 | 3.21 | 5.56 | 5.40 |
| 2026F | 6.20 | 8.38 | 3.21 | 5.57 | 5.40 |
| 2027F | 6.20 | 8.47 | 3.21 | 5.57 | 5.40 |
| 2028F | 6.20 | 8.53 | 3.21 | 5.57 | 5.40 |
| 2029F | 6.20 | 8.58 | 3.21 | 5.57 | 5.40 |
| 2030F | 6.20 | 8.61 | 3.21 | 5.57 | 5.40 |

## 12. Simulated Energy Demand until 2030

After generating the forecasted values, we further simulate the results based on our regression model. Since petroleum product and electricity demand growth rates depend on their substitution relationship and GSDP growth rate, based on our elasticity coefficients (reflected from regression coefficient estimates), we have tried to simulate the series for only petroleum and electricity consumption demand till 2030, given the goal of the state to achieve zero net carbon emissions by 2070. In light of the aim to achieve net zero carbon emission by 2070, the objective of the study is to assess, whether the energy demands are consistent with this goal. The growth rates of two energy demand pattern are simulated based on our forecasted GSDP average growth rate of 6.2%. In an alternative scenario, assuming that the predicted GSDP growth rate of 6.2% might not be forecasted with 100% precision as this is based on a simple and parsimonious model where the GSDP series undergoes severe fluctuations time to time, we further assume that it may deviate with an upper margin of 1% rate. Therefore, we assume the GSDP to grow at 7.5% rate. Under this two-alternative scenario, we have simulated the energy demand growth rate patterns for the state to see the path of energy consumption demand values what would happen by the year 2026 and by 2030.

The 2nd column of Table 8 presents simulated values of petroleum consumption on assumed GSDP growth rate of 6.20% and electricity consumption growth at 5.05% till 2025 from 2020–21 and further at 5.573 % from 20026 till 2030. The 3rd column in Table 8 presents simulated values of electricity consumption based on assumed GSDP growth rate of 6.20% and petroleum consumption growth rate of 3.78% from 2020–21 onwards throughout. The 4th column in Table 8 provides simulated values of petroleum consumption demand on assumed GSDP growth rate of 7.5% and electricity consumption growth at 5.05% till 2025 from 2020–21 and further at 5.573 % from 20026 to 2030. The 6th column in Table 8 provides the simulated values

**Table 8**
**Simulated values of energy demand (Petroleum Products and Electricity consumption growth rates)**

| Year | Petroleum Products consumption growth rate with assumed GSDP growth rate of 6.2% | Electricity consumption growth rate with assumed GSDP growth rate of 6.2% | Petroleum Products consumption growth rate with assumed GSDP growth rate of 7.5% | Electricity consumption growth rate with assumed GSDP growth rate of 7.5% |
|---|---|---|---|---|
| 2020S | 3.84 | 5.55 | 5.38 | 6.28 |
| 2021S | 3.84 | 5.55 | 5.38 | 6.28 |
| 2022S | 3.84 | 5.55 | 5.38 | 6.28 |
| 2023S | 3.84 | 5.55 | 5.38 | 6.28 |
| 2024S | 3.84 | 5.55 | 5.38 | 6.28 |
| 2025S | 3.84 | 5.55 | 5.38 | 6.28 |
| 2026S | 3.69 | 5.65 | 5.23 | 6.38 |
| 2027S | 3.69 | 5.65 | 5.23 | 6.38 |
| 2028S | 3.69 | 5.65 | 5.23 | 6.38 |
| 2029S | 3.69 | 5.65 | 5.23 | 6.38 |
| 2030S | 3.69 | 5.65 | 5.23 | 6.38 |
| Average growth rate over 11 years | 3.77 | 5.59 | 5.31 | 6.32 |

**Note:** S stands for simulated values based on forecasted values of exogenous variable like GSDP. The simulation is based on our assumed growth rate variations presented in respective columns and regressions estimations presented in Table 4.

of electricity consumption based on an assumed GSDP growth rate of 7.5% and petroleum consumption growth rate of 3.78% from 2020–21 onwards throughout.

The simulated values of energy consumption demand on petroleum and electricity in Kerala suggests acceleration of consumption demand for petroleum products and electricity until the year 2030 where electricity demand would grow at a higher rate than the petroleum demand. Electricity being partly generated from the use of hydro and other renewable resources (solar and wind), if the generation capacity of the state can be further enhanced, that would keep down the petroleum demand under check. This is based on the substitutional elasticity responses of both the energy demand as indicated in our regression model. This would help the state maintaining the environmental quality by controlling the levels of emissions.

## 13. Conclusion and Policy Implications

The study verified the dynamics of growth rates of energy consumption, output and carbon emissions in a high human development achiever state of India, i.e. in Kerala. It provides an interesting backdrop since Kerala's emission is very meager than the national average. We rely on data from various sources including the EPW research foundation, GHG platform, EMC-CDS study report and KSEB statistics to construct a unique dataset. It used regression, Granger causality and forecasting techniques for the main findings. Given the consistency in our empirical estimates, we find that faster economic growth exerts relatively greater demand for petroleum consumption than the electricity. While regression results point out, only the petroleum product consumption positively drives GSDP growth rather than electricity consumption growth influencing the same but after incorporating the time dynamics into their relationship (through lagged effects), Granger causality reveals that electricity consumption also contributes to economic growth. Although the regression result reveals that growth rates of transportation, storage and communication activities, contemporaneously lead to $CO_2$ emission, but the same is not evident with our ganger causality results. Most interestingly, our results also suggest that electricity and petroleum product consumption are substitutes to each other. This finding may be driven by conscious decision of people to switch to electricity consumption due to greater emissions from petroleum consumption. This change is evident from high growth rate in number of e-vehicles plying into streets of Kerala on a day-today basis suggesting potential demand for these segments of vehicles in near future.[7]

The strong substitutability between electricity and petroleum consumption could be explained by the fact that when growth of petroleum consumption is not at its same pace, but electricity consumption is increasing at a faster pace led due to acceleration in the use of e-vehicles. The desire to reduce petroleum consumption is not only led by environmental consciousness of reducing emissions but also due to its increasing cost of it led by upward price movement. Thus, prediction of this relationship seems to be realistic and reasonable.

However, the insignificance of electricity consumption demand on GSDP growth also could represent the delayed effect of electricity consumption on GSDP growth. This is because per capita electricity consumption in India is very negligible comparing the advanced economies. There are capacity constraints to generate and distribute and there is also lesser demand of it because of low per capita incomes and structural constraints into it. Government should provide greater subsidies in e-vehicle segments to encourage greater production and use of it in the Indian roads. However, one striking question it gives rise to if greater electricity is consumed for industrial uses, this may greatly add to the GSDP but if it is only consumed by households, how much additional GSDP can be generated.

While drawing the above conclusion, nevertheless, there are limitations associated with our study which remained unaddressed due to data unavailability. Since Kerala is not an industrial state, rather a service dominant economy where its share constitutes more than two-thirds of GSDP, and the state imports significant volume of

[7] The number of electric vehicles in Kerala has increased from a mere count of 472 EVs in 2019 to a substantial 39,564 electric vehicles in 2022. This spike in EV sales illustrates Kerala's steady and notable advancement in embracing electric mobility. The sales of electric vehicles in Kerala increased by 7.92% in 2023 from 4.6% in 2022.

manufactured goods from other industrial states including electricity. These determines both levels and growth rates of $CO_2$ emissions. This might have implications for the climate changes in those regions as well. However, this study does not account for the extent of $CO_2$ emissions and climate change caused by Kerala into those regions. While investigating the role of energy consumption in Kerala's GSDP growth, the study could not incorporate other key macro determinants of growth like private investment and public investment influencing the growth rate. This is purely on account of limited number of observations in our data set.

The study addresses a very relevant issue from a policy perspective. One of the main findings of the study is that transportation services contribute to the rising emissions. Rising demand for petroleum products requires immediate attention. Curbing the demand would require a roadmap to increase the reliance on renewable sources of energy. This objective is achievable only if the government, industry and other participants work in synergy with each other. In this line, the current study paves the way for policies and incentives that can promote green technology usage and cleaner production processes. At the policy level, one can examine the projected and simulated energy demand to assess the consistency of the projections with a net zero emission target of Kerala by 2070.

Further, petroleum consumption drives economic growth, and transport as one of the important sectors plays out a crucial role in supply chain for all sectors of the economy, including agriculture, manufacturing and services. Given the fact that tourism is currently an engine of growth of Kerala and will continue to be so in the coming years as per Kerala's development Report 2020–21, the transport sector is expected to grow faster in forthcoming years. Policymakers need to find a way-out for alternative fuels and improve energy efficiency in this sector. Presently, the common alternatives of conventional fossil-fuel in transport are electric vehicles or biofuels. Electric vehicles reduce local air pollution. But it is mostly dependent on power generated from fossil-fuel produced somewhere in the country, so unless the state reduces fossil-fuel dependency in power generation and shifts to renewable energy generation by encouraging green financing of green investment and infrastructure for a cleaner and sustainable environment, electric vehicle will have a limited capacity of reducing overall GHG emissions. The fuels that are currently used for transportation as an alternative biofuel are biodiesel and bioethanol. Despite the usefulness of these fuels for adapting low-carbon pathway, these are generally produced from feedstock, which are also used for food production and feed production, and hence, large scale production can threaten food security. Apart this, increase in biofuel production might require land-use change, i.e. converting forest, wetlands or peatlands to agricultural land, resulting in loss of possible benefits in reduction of emission, especially in a state like Kerala, where land availability is a huge concern. The 3rd or 4th generation, namely algae-based biofuel, yet to have a footing into the Indian context. For alternative fuels like green hydrogen and fuel cell vehicles, cost-efficiency is a pre-requisite for large-scale deployment. Reducing dependence on fossil fuel by promoting reliable renewable energy sources and improving battery storage to meet required energy demand and energy security calls for greater green investment. This can help to transit to using electric vehicles, which can play major role in reducing emissions from transport sector at the present states of technology. But then, the policymakers must be prepared for environmental sustainability issues regarding extracting mining materials for battery production and battery recycling.

Kerala imports major percentage of coal-fired electricity energy from other neighbouring states. Although this energy reliance keeps $CO_2$ emission under check within the state, but it releases emission into the neighboring states. Kerala is most likely to face the shortage of cheap power supply when all the states adopt a low carbon pathway or net zero carbon pathway by 20270 similar to Kerala. Therefore, the state needs to explore its alternative potential of extracting energy from non-fossil fuels, if other states cannot provide sufficient energy supplies on a regular basis during the transition phases. Kerala needs to exploit new and unconventional renewable energy sources like waste to energy, offshore wind farm, floating solar firms on water bodies etc. These will reduce its reliance on fossil fuels to continue with its economic growth.

Since Kerala majorly imports electricity from other neighbouring states and hence emission related to electricity generation and consumption does not arise significantly or add to the emission in Kerala. Transportation demand is quite insignificant in Kerala and hence emission arising from it is quite little in the absence of industrial/manufacturing base in Kerala. However, the state can still incentivise deployment of more mass rapid transportation system and introduce more e-vehicles by asking greater subsidies from the center as environment of the state will have an external impact. When Kerala undertakes such regulatory measures of reducing $CO_2$, the nation as a whole would benefit from such positive measures. Therefore, center along with the states have major responsibilities to address the environmental impact of increasing use of conventional energy components. The state can also provide more subsidies on buying of environmental compliance goods like installation of solar panels on building rooftops of households and buying e-vehicles and other power saving technologies and implements.

## 14. Directions for Future Research

Examining the issue for a sub-national context posed a challenge on account of availability of limited number of observations. Thus, we could not incorporate other key variables influencing economic growth and energy demand. Future studies can incorporate role of real private and public sector investments in economic growth and energy models of subnational economies, while examining various components of renewable as well as non-renewable energy demand. For better policy perspective, one can also introduce the structural changes by introducing contribution of different sectors in total output and growth rate of the economy. Various energy intensive consumption sub-sectors and economic activities (measured in output) of respective sub-sectors may also be explored for a detailed policy insight for Kerala and other sub-national economies but the data availability put a predominant constraint for an expansive policy analysis at the sub-regional level. With more availability of data, future research can overcome these constraints.

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## 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 sharing is not applicable to this article as no new data were created or analyzed in this study.

## Author Contribution Statement

**Hrushikesh Mallick:** Conceptualization, Software, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization, Supervision, project administration. **Pulikottile Louis Beena:** Conceptualization, Supervision, Project administration. **Ritika Jain:** Methodology, Investigation, Data curation, Visualization, Supervision. **Sanjib Pohit:** Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization, Supervision. **Chetana Chaudhuri:** Methodology, Software, Supervision.

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## Appendix

**Figure A1**
**Population growth in Kerala**

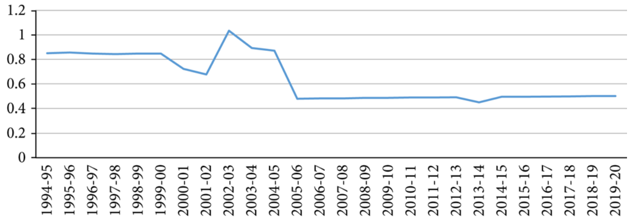


**Table A1**
**Bi-variate correlation matrix of growth rates of all variables**

| | GRAND TOTAL EMMISSIONS | GSDP | PETROLUEM PRODUCTS CONSUMPTION | TOTAL ELECTRICITY CONSUMPTION | TRANSPORT & STORAGE OUTPUT | TRANSPORT EMMISSIONS | RAILWAY TRACTION ENERGY |
|---|---|---|---|---|---|---|---|
| GRAND TOTAL EMMISSIONS | 1.00 | | | | | | |
| GSDP | 0.12 | 1.00 | | | | | |
| PETROLUEM PRODUCTS CONSUMPTION | 0.09 | 0.49* | 1.00 | | | | |
| TOTAL ELECTRICITY CONSUMPTION | -0.02 | 0.30 | -0.02 | 1.00 | | | |
| TRANSPORT & STORAGE OUTPUT | 0.53* | 0.22 | -0.06 | 0.49* | 1.00 | | |
| TRANSPORT EMMISSIONS | 0.43* | 0.18 | -0.24 | 0.52* | 0.46* | 1.00 | |
| RAILWAY TRACTION ENERGY CONSUMPTION | 0.16 | 0.30 | 0.04 | 0.27 | 0.51* | 0.32 | 1.00 |

**Note:** *Denotes a strong relationship between variable pairs representing in respective rows and columns. This is based on t-statistic of the correlation coefficients. The correlation is computed utilising the available data from 2006–07 to 20019–20.

**Table A2**
**Unit root test results**

| | In levels | |
|---|---|---|
| **Variables** | **ADF** | **PP** |
| GSDP growth rate | −3.18* | −3.18* |
| Transportation output growth rate | −2.05** | −12.80* |
| Petroleum consumption growth rate | −4.30* | −4.30* |
| Electricity Consumption growth rate | −3.56* | −3.56* |
| $CO_2$ Emission growth rate | −5.07* | −2.18 |

**Note:** The critical values for rejecting the null hypothesis are −3.95 at 1% level and −3.08 at 5% level.