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TRENDS IN CARBON EMISSIONS AND RENEWABLE ENERGY USAGE

POOJA SENGUPTA*

Information Systems and Business Analytics, Indian Institute of Management, Ranchi Ranchi, India

Email: pooja.sengupta@iimranchi.ac.in

BHASWATI GANGULI*

Department of Statistics, University of Calcutta, India

Email: bgstat@gmail.com

DASAUKI MUSA

Lecturer II, Department of Economics, Babcock University, Remo, Nigeria

BUSAYO T OLANREWAJU

Research & Market Insights Supervisor, KPMG, Nigeria

OLUSANYA E. OLUBUSOYE

Department of Statistics University of Ibadan Ibadan, Oyo State, Nigeria

SUMMARY

The purpose of carrying out this study was to explore the trends and inter-linkages between CO_2 emission and RE share of total energy between 1990 and 2015. The United Nations' Sustainable Development Goal 7 is to ensure access to affordable, reliable, sustainable, and modern energy for all. With these targets in mind, we have tried to answer questions like how has the global RE share of total energy changed over time, does the pattern of RE change over time affect CO_2 emissions, and has access to clean energy changed significantly over time? The findings of this study has established that there is a general increasing trend in RE and that is associated with diminished trend in CO_2. Looking at the access to clean energy between rural and urban sectors and they presented starkly different time trend with almost twice as large a percentage of population with access to clean energy in the urban areas than the rural.

Keywords and phrases: Renewable energy, Carbon emission, mixed effects model, energy access.

* Corresponding author

1 Introduction

The United Nations made an endeavour to formalise the blueprint for prosperity in the lives of all people around the globe. Among these were poverty alleviation, zero hunger, gender equality, good health and well-being, clean drinking water, etc. The United Nations outlines seventeen such goals, to improve the living conditions and remove deprivation of people from developed as well as developing nations. On this list of goals, seventh is affordable and clean energy. Sustainable Development Goal 7 (SDG 7) of the United Nations is to ensure access to affordable, reliable, sustainable and modern energy for all. Related targets include

- Target 7.1: By 2030, ensure universal access to affordable, reliable and modern energy services.
- Target 7.2: By 2030, increase substantially the share of renewable energy (RE) in the global energy mix.
- Target 7.b: By 2030, expand infrastructure and upgrade technology for supplying modern and sustainable energy services for all in developing countries, in particular least developed countries, small island developing States, and land-locked developing countries.

A related target for SDG 13 on combating climate change is

- Target 13.2: Integrate climate change measures into national policies, strategies and planning,

with the corresponding indicator being total greenhouse gas emission. The objective of this paper is to study the effectiveness of the SDG goals undertaken by the nations who are members of the International Solar Alliance (henceforth will be mentioned as ISA).

Figure 1 displays the heterogeneity in country specific trajectories of RE shares of total national energy consumption and per capita CO_2 emission between 1990 and 2014 and provides the motivation for this paper. It is clear from the plot that the average trend in CO_2 emission is slightly increasing. We can see that most countries are clustered within the range of 0 to 5 metric ton per capita of CO_2 emission. And there are a few where emission is high and is in the range of 15 to 20 metric ton. But the overall trend for most countries is slightly increasing emission over the years. Similarly if we look at the trend of RE share of total energy consumption across various countries, the values range from very low (1%) to very high (close to 90 %). Developed nations such as the United States, the United Kingdom and Australia have higher CO_2 emissions as compared to other countries. However, there appears to be a steady decrease post 2009 for all three countries. For several African nations, such as Ghana, Congo, and Nigeria, per capita emissions appear to be stable over time. A dramatic increase is observed for China while a modest increase is observed for India, Brazil and Argentina. Interestingly, the three countries with the highest emissions levels also appear to have the lowest RE share of total energy consumption, although each shows a gradual increase post 2007. When compared to the country-specific trends in RE share, the average overall has a downward trend where in 1990 the RE share of total energy was about 45 %, it gradually decreased to around 36 % in 2015. Similarly, the average trend in CO_2 emission is more or less stable in the range of 4.8 metric ton per capital in 1990 to 5.10 metric ton per capita in 2015 with no majorly discernible increase or decrease in the years in between.

Now, according to studies on SDGs, there are several challenges involved in achieving most of them. Some of the foremost reasons are instability in the relations between nations, the ever changing economic scenario, and other political contingencies. Also, implementing SDGs across nations sometimes pose a problem when the local contexts are taken into account. For instance, the rural and urban segments of a nation function differently and taking a unifying approach to implementation of SDGs in such cases becomes difficult. As another major impediment to attaining the SDGs is the governance of nations to transform developmental programmes into a sustainable long-term project. The same problems arise when addressing SDG 7 and this explains to some extent the varying patterns of CO_2 and RE share across the various ISA member nations. The predictive models used in this paper have a two-fold application. The model outcomes depict the overall trend in CO_2 and RE share over time but also captures the country-specific patterns over the 26 year time period between 1990 to 2015.

In this paper, we shall use statistical modelling of country level data on renewable energy and emissions from the World Bank Open Data repository to answer the following research questions:

- How has the global RE share of total energy changed over time period 1990 to 2015?
- Does the pattern of RE share change over time affect CO_2 emissions?
- Has access to clean energy improved over time?

Subject specific modelling via the use of linear mixed models (LMM) will allow us to capture global trends as well as characterise the extent and nature of heterogeneity in country specific profiles.

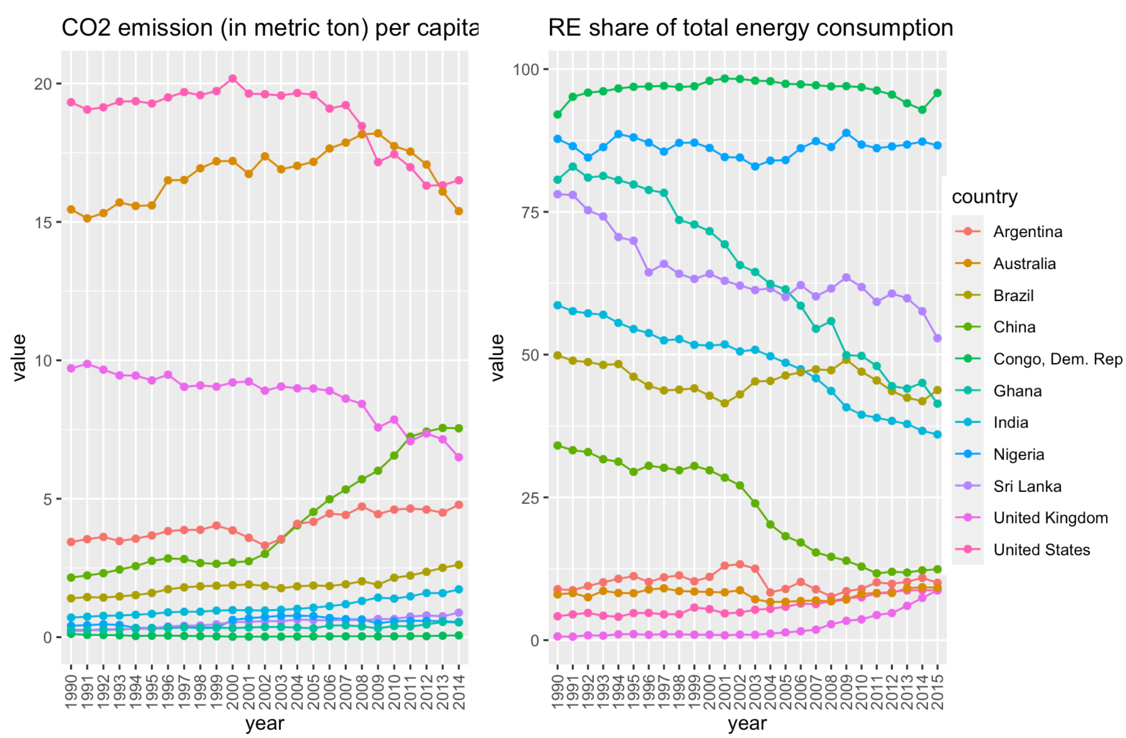


Figure 1: Global and country specific trajectories in RE share of total energy consumption CO_2 emission between 1990 - 2014.

The rest of the paper is structured as follows. Section 2 outlines the review of extant literature on the CO_2 and RE share, their trends and the way forward. Section 3 describes the data used in this study. Section 4 discusses the details of the Linear mixed model (LMM) used to analyse the country-specific data and the clustering techniques used to group countries with similar trends in CO_2 and RE share. Section 5 discusses the insights and findings from the analysis of data on the ISA member countries. Section 6 outlines the summary of the findings and conclusion.

2 Literature Review

Renewable energy (RE) is collected from resources (Ellabban et al. (2014)) that are naturally replenished on a human timescale. In contrast, fossil fuels like coal and petroleum are used up faster than can be replenished. Recent decades have witnessed significant increase in RE investment, improvement in RE technology and reduction in the cost of implementing RE practices. This is partially explained by the fact that, increased global energy consumption has raised global energy demand by almost twice its average growth since 2010. In the midst of this rising energy demand, energy related carbon emissions have also increased and carbon dioxide (CO_2) emissions resulting from the burning of fossil fuels, is considered the largest number contributor to the Greenhouse Effect.

The literature on time trends and association between renewable energy usage and emissions shows heterogeneous findings and generally consist of studies of single countries or small groups of relatively homogeneous countries. Lean and Smyth (2010) found evidence that increase in electricity consumption causes higher CO_2 emissions in five member countries of the Association of Southeast Asian Nations (ASEAN), namely Indonesia, Malaysia, Philippines, Singapore and Thailand. Nguyen and Kakinaka (2019) applied panel co-integration analysis to examine the relationship between the consumption of RE and CO_2 emissions in 107 countries. The result shows that CO_2 emissions and output will reduce when RE consumption increases. Akintande et al. (2020) use Bayesian Model Averaging for 5 populous African countries and reports that population growth, urban population, energy use, electric power consumption, human capital determinants are positively related to RE consumption.

A study conducted by Shan et al. (2017) concludes that China is the world's largest energy consumer and CO_2 emitter. In China, cities contribute 85% of the total CO_2 emissions and thus are considered as the key areas for implementing policies designed for mitigating CO_2 emission in the country. Shahbaz et al. (2013) used co-integration to investigate the effect of energy use on economic growth in China and found evidence of bidirectional causality.

However, Apergis (2016) conducted a panel study of the relationship between CO_2 emissions and Gross domestic Product (GDP) in 15 countries and reported results counter-intuitive to environmental Kuznets theory for 3 countries. Alam et al. (2016) examine the relationship between CO_2 emissions, income and energy consumption in India, Indonesia, China and Brazil. Findings show that an increase in income and energy consumption has increased CO_2 emissions in India and Brazil. This result is significant for China and Indonesia in both short-run and long run. However, Aye and Edoja (2017), using a threshold model, found a negative relationship between economic growth and CO_2 emissions in regimes with low growth and a positive relationship for regimes with high growth. Lu (2017) examined 42 ASEAN countries and finds evidence of a causal relationship for the Philippines, Pakistan, China, Iraq, Yemen, & Saudi Arabia. Inglesi-Lotz and Dogan (2018) found unidirectional causality to CO_2 emissions and RE energies, and a unidirectional causality from CO_2 emissions and nonRE energy to trade in 10 Sub-Saharan Countries.

However, Olubusoye and Musa (2020) tested the environmental Kuznets curve hypothesis in 42 African countries but the hypothesis is rejected in over 79% of the sample. This result implies that economic growth will induce higher CO_2 emissions in most African countries if no mitigation measure is put in place. The study recognized the role of policy making, RE and investment in new technology in combating climate change by mitigating growth in CO_2 emission. Olanrewaju et al. (2019) examine the determinants of RE in 5 populous and biggest economies in each region in Africa from 1990-2015 and conclude that an increase in RE consumption will depress energy intensity. Awodumi and Adewuyi (2020) The study found evidence that petroleum and natural gas consumption per capital have an asymmetric impact on GDP and CO_2 per capita except in the case of Algeria. Non-RE reduces carbon emissions in Nigeria but promotes growth and reduces emissions in Gabon. The result is mixed for Egypt and Angola.

There have been certain studies that considered panel data to study the time wise trend in CO_2 emission and RE share. Sharif et al. (2019) have concluded from their study that renewable and non-renewable energy consumption and carbon emission are integrated over time in the long-run and over time renewable energy has a negative and significant impact on environmental degradation. A time series analysis of renewable energy, carbon emission and financial development of Middle East and North African countries by Charfeddine and Kahia (2019). The authors suggested through their results that both renewable energy consumption and financial development can only mildly explain CO_2 emission and economic growth in these countries. Thus, they indicate that both financial development and the renewable energy sectors can very weakly contribute to environmental quality improvements and economic growth. But the growth in renewable energy also calls for the distribution of the energy. In some countries, making the renewable energy accessible to the populace. Gielen et al. (2019) have reported in their findings that the share of renewable energy in total energy supply would rise from 14% in 2015 to 63% in 2050. But it is also imperative to make this energy accessible. In their paper, Murshed (2020) investigated and found out the non-linear impacts of ICT (Inner Circle Trading) trade on the future of renewable energy transition, improving energy use efficiencies, increasing access to cleaner fuels, and diminishing carbon dioxide emissions across selected South Asian economies, namely, Bangladesh, India, Pakistan, Sri Lanka, Nepal, and Maldives.

This review further highlights the diversities in trajectories of relevant indicators and illustrates the need for a large pooled study of global and country specific trends in renewable energy usage and CO_2 emissions

3 Data Description

We shall consider the group of all 1107 member countries of the International Solar Alliance (ISA). The alliance is a treaty-based inter-governmental organization initiated by India as a common platform for increased deployment of solar energy technologies as a means for bringing energy access, ensuring energy security, and driving energy transition in its member countries. A majority of these 117 nations are located in the 'sunshine belt' between the Tropics of Cancer and Capricorn. Other members include the United States of America, the United Kingdom, Australia and France.

We shall consider historical data for these countries on CO_2 emission, percentage of population with access to clean energy, percentage of the rural and urban population with access to electricity and RE share of the total electricity consumption for 1990 – 2015. The data is obtained from the SE4ALL database created by the World Bank to support the "Sustainable Energy for all (SE4ALL)" initiative, launched in 2010 by the UN to work towards its 2030 target to ensure universal access to modern energy services and to double the share of renewable energy in the global energy mix. A detailed description of the variables used in this study are presented in Table 1.

Table 1: Description of the variables in the study

Variables	Description	Units
RE share	Renewable energy share of total electricity output	% of total energy consumption (kWh)
$Access_{urban}$	Access to electricity in urban sector	% of urban population
$Access_{rural}$	Access to electricity in rural sector	% of rural population
$Access_{total}$	Access to energy from zero-emissions through energy efficiency ("EE") measures sources ("renewables") and energy saved.	% of population
CO_2	Carbon emissions per capita measured as the total amount of carbon dioxide emitted by the country as a consequence of all relevant human activities, divided by the population of the country	metric tons per capita
$CO_{2combustion}$	CO_2 emissions from electricity and heat production total	% of total CO_2 emissions from fuel combustion
$CO_{2manufacturing}$	CO_2 emissions from manufacturing industries	% of total CO_2 emissions from manufacturing industries
$CO_{2buildings}$	CO_2 emissions from residential buildings	% of total CO_2 emissions from residential buildings
$CO_{2transport}$	CO_2 emissions from transport	% of total CO_2 emissions from transport

The table 2 provides the univariate descriptive measures of the variables used in this study. The table is followed by the correlation plots for four exemplar countries. In this study we wish to explore how global RE share of total energy has changed over time, whether RE share change over time can affect CO_2 emission, and whether access to clean energy has changed in the countries over time. To that end, we explore the pairwise correlation between the variables chosen for this study. The correlation plots for four chosen countries are shown in Figure 2.

4 Methodology

4.1 Subject specific modelling

Subject specific models are a class of regression models commonly used to model longitudinal data in presence of subject specific heterogeneity. Such models provide us with overall predictions for population averages as well as subject specific predictions for each subject considered in the dataset.

Subject specific models are special cases of the general Linear Mixed Model (LMM) which can be represented by the regression equation,

$$y = X\beta + Zu + e$$

where y is a $NX1$ response variable, X is an NXp design matrix, β is a $pX1$ column vector of fixed effects, Z is an NXq design matrix for the random effects and u is a $qX1$ vector of random effects and e is a random

Table 2: Univariate descriptive measures of the variables used in the study

Variable	N	Mean	Std. dev.	Min.	Max.
CO2_emission_kt	2,771	1,65,306.80	7,77,280.23	7.334	1,02,91,926.88
CO2_emission_metric_ton	2,771	2.991	4.967	0.011	36.092
Population	3,006	4,53,88,371.66	16,25,56,837.23	8,913.00	1,37,86,65,000.00
GDP	3,006	6,984.64	11,311.30	164.337	68,780.59
Access_to_clean_energy	1,901	48.061	38.428	0.15	100
Electricity_access_rural	2,710	56.834	37.665	0.001	100
Electricity_access_urban	2,965	80.182	25.266	0.01	100
RE_share_of_total_electricity_output	2,894	33.463	35.018	0	100
Total_energy_consumption	2,894	17,18,501.12	70,19,723.30	0	7,31,83,146.53

error term. We make the distributional assumption that,

$$\begin{pmatrix} u \\ e \end{pmatrix} \sim MVN\left(\begin{pmatrix} 0 \\ 0 \end{pmatrix}, \begin{pmatrix} G & 0 \\ 0 & \Sigma \end{pmatrix}\right).$$

where G and Σ are matrices of variance and covariance parameters. The Maximum Likelihood Estimator of β is given by

$$\widehat{\beta} = (X^{'}V^{-1}X)^{-1}y \sim MVN(\beta, X^{'}V^{-1}X)^{-1})$$

where $V = ZGZ^{'} + \Sigma$. The Σ in the mixed effects model is set to take the Auto-regression(1) structure in this model fitting. The form that Σ takes in the AR(1) structure is as follows;

$$\begin{pmatrix} \sigma^2 & \sigma^2\rho & \sigma^2\rho^2 & \dots & \sigma^2\rho^n \\ \dots & & & & \\ \sigma^2\rho^n & \sigma^2\rho^{(n-1)} & \sigma^2\rho^{(n-2)} & \dots & \sigma^2 \end{pmatrix}$$

The Best Linear Unbiased Predictor (BLUP) of u is given by;

$$\widehat{u} = GZ^{'}(ZGZ^{'} + \Sigma)^{-1}(y - X\widehat{\beta})$$

These can be used to obtain the BLUP of any linear parametric function. G and Σ, if unknown, can be estimated using Maximum Likelihood (ML) or Restricted Maximum Likelihood (REML) estimation. Tests of hypotheses and confidence estimation can be derived based on asymptotic distributional theory. The above model can be used, for example, to model the changes in RE share or CO_2 emission over time, as follows:

$$\text{RE} \quad \text{share}_{ij} = (\beta_0 + u_{i0}) + (\beta_1 + u_{i1})\text{Year}_{ij} + e_{ij};$$

where RE share$_{ij}$ is the RE share of the i^{th} country in the j^{th} year with $i = 1, \dots, 117$ and $j = 1, \dots, 26$.. Here, β_0 and β_1 are fixed effects and represent the global average RE share at baseline and the global annual rate of change, repectively. u_{i0}'s and u_{i1}'s are random effects and represent the deviations in the same quantities for the ith country, respectively. In this study the design matrix X and Z consists of the time variable. Through the X, the model defines the overall fixed effect of time on RE share and Z captures the country-specific random effects. Similarly, the following subject specific model was fitted to model the dependence of CO_2 on RE share:

$$\mathrm{CO}_{2ij} = (\alpha_0 + v_{i0}) + (\alpha_1 + v_{i1})\mathrm{Year}_{ij} + +\alpha_2 \mathrm{RE\ share}_{ij} + \alpha_3 \mathrm{RE\ share}_{ij} \times \mathrm{Year}_{ij} + e_{ij}$$

where CO_{2ij} is the CO_2 emission for the i^{th} country in the j^{th} year, α_0, α_1, α_2 and α_3 are fixed effects parameters and v_{i0}'s and v_{i1}'s are random effects subject specific deviations. Note that the model allows for an

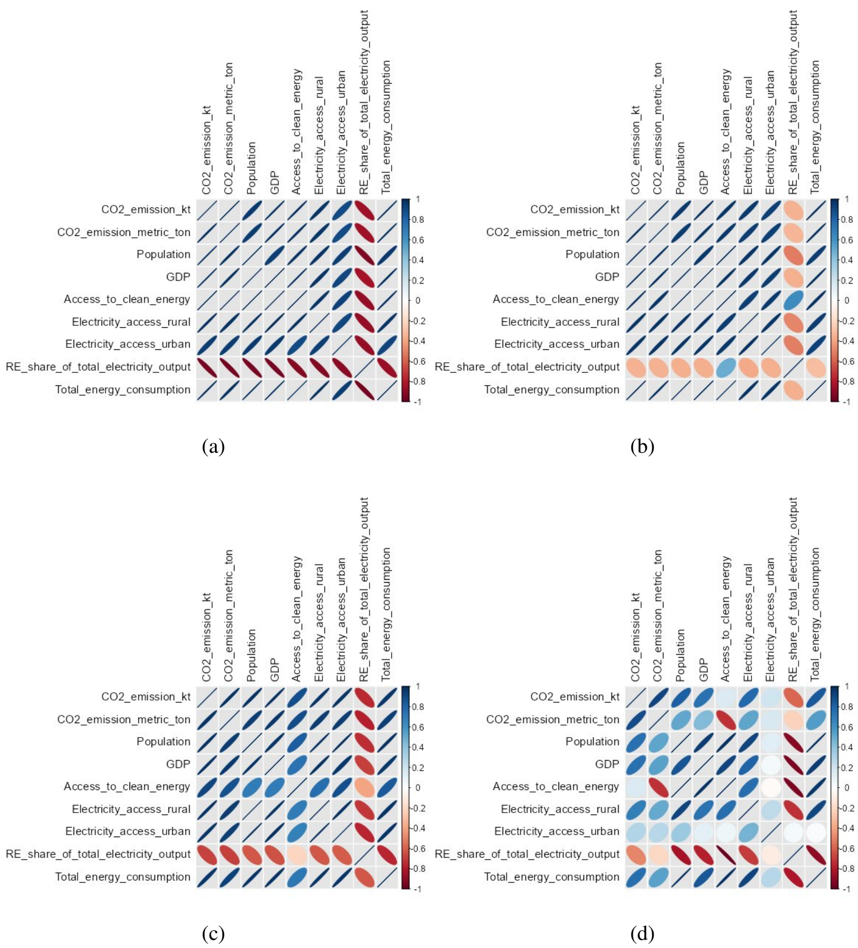


Figure 2: Country-specific correlation plots different countries: (a) Bangladesh (b) India (c) Malaysia (d) Nigeria

interaction between the effect of changes in RE share and time.

The LMM can also be tweaked to model a bivariate regression of the form, The model used to fit the regression is;

$$\text{Rural Access}_{ij} = (\gamma_0 + w_{1i0}) + (\gamma_1 + w_{1i1})\text{Year}_{ij} + e_{1ij}$$
$$\text{Urban Access}_{ij} = (\delta_0 + w_{2i0}) + (\delta_1 + w_{2i1})\text{Year}_{ij} + e_{2ij}$$

where Rural Access and Urban Access are respectively the percentages of rural and urban population with access to clean energy in the i^{th} country in the j^{th} year. γ_0, γ_1, δ_0 and δ_1 are fixed effects coefficients and $(w_{1i0}, w_{1i1}, w_{2i0}, w_{2i1})'$'s are 4×1 dimensional multivariate normal terms representing subject specific deviations and are assumed to have a multivariate normal distribution with zero mean vector and unknown variance covariance matrix. We allow for correlation between rural and urban access percentages within each country as both are likely to share some common determinants.

4.2 Clustering

Clustering of country specific random effects will yield relatively homogenous groups of countries with similar patterns over time. The K-Medoids algorithm is used for this purpose. Unlike the former, the K-medoid algorithm is less sensitive to outliers, and hence produces more reliable representatives for each cluster. A medoid refers to an object within a cluster for which average dissimilarity is minimised within the cluster and which can be considered as a representative value of the response for the cluster. The Partitioning Around Medoids (PAM) algorithm is based on the search for K representative medoids among the observations of the data set, using the following steps:
Build phase:

1. **Select k observations as the medoids.** We choose some values of k starting with one and calculate its average silhouette score. The silhouette value is a measure of how similar an observation is to its own cluster as compared to other clusters. Calculation of the silhouette score is done as follows;

   (a) Compute a_i: The average distance of an object with all other objects in the same clusters.

   (b) Compute b_i: The average distance of an object with all the objects in the cluster closest to its own.

   (c) Compute s_i: silhouette coefficient or i^{th} point as,

   $$s_i = \frac{b_i - a_i}{max(b_i, a_i)}$$

   The optimal value of k is that which produces the highest average silhouette score.

2. **Calculate the dissimilarity matrix.** Dissimilarities are calculated between all pairs of objects using the Euclidean or the Manhattan distance. The Euclidean distance is calculated as the square root of the sum of squared differences and the Manhattan distance is calculated as the sum of the absolute distances. Although more popular, the Euclidean distance is unduly affected in case there are outlier in the data. In such cases, the Manhattan distance provides a more robust measure.

3. **Assign every object to its closest medoid.** The closeness of an object to its medoid is measured by the dissimilarity

Swap phase:

4. For each cluster search we check if any of the observations in a cluster decreases the average dissimilarity coefficient within the cluster.

5. Once we find such an observation, we select the entity that decreases this coefficient the most as the new medoid and repeat the procedure.

For the analysis done in this study, the trend of CO_2 emissions and RE share over time and also the country-specific effect of time on the relevant variables are deliberated about. However, there are varied effects of the independent variables in the model used in this study. Also the countries all have their unique trends in CO_2 emissions and RE share over time. To understand the homogeneous groups of nations that show similar patterns in the changing scenario in terms of CO_2 emissions and RE share over time, we use the estimated model coefficients to create clusters with similarities. The same is depicted in figures 4 and 7.

5 Results

In this section, we discuss the results of our analysis in the context of the three research questions outlined in the introduction. The following subsections have been dedicated to the discussion of the results from the various model fittings.

5.1 How has RE share of total energy changed over time globally?

To address this question, we have used the LMM model with time as the independent variable. The model takes the following form;

$$\text{RE}\quad\text{share}_{ij} = (\beta_0 + u_{i0}) + (\beta_1 + u_{i1})\text{Year}_{ij} + e_{ij};$$

where RE $\quad$ share_{ij} is the RE share of the i^{th} country in the j^{th} year with $i = 1, \ldots, 117$ and $j = 1, \ldots, 26$.. Here, β_0 and β_1 are fixed effects and represent the global average RE share at baseline and the global annual rate of change, respectively. u_{i0}'s and u_{i1}'s are random effects and represent the deviations in the same quantities for the ith country, respectively. Results from fitting the this model indicates that the average RE share in 1990 was 40% and that on average, the RE share decreases annually by 0.17% (p-value $= 0.098$). However, there is considerable heterogeneity across countries. Baseline RE shares in 1990 range from 1.8% for Botswana to 99.6% for Paraguay while the rate of change ranges from an annual reduction of 1.4% to an annual increase of 1.3%. Greater insight into the patterns can be obtained by clustering the subject specific coefficients following the methods in section 4. This leads to identification of six distinct clusters of countries. Cluster specific patterns are summarised in Table 3.

Cluster patterns have also been illustrated in Figure 3. Table 4 lists countries by cluster. The identification of groups of member countries with similar pattern in RE share can help the ISA in policy formulation by addressing issues which dampen RE growth (in case of countries where RE growth is negative with respect to time) or helping other members to emulate the RE practices of countries where RE growth is satisfactory.

Table 3: Characterisations of patterns in RE share trends

Cluster no.	RE share in 1990	Annual change in RE share	Characterisation
1	3.092	0.037	High baseline and steady increase
2	1.200	-0.0167	Moderate baseline but steady decrease
3	0.638	-0.0191	Moderate baseline and modest to no change
4	0.956	0.0153	Moderate baseline and steady increase
5	1.425	-0.0136	Moderate baseline with little change over time
6	0.785	-0.0024	Moderate baseline but steady decrease

5.2 Do countries with increasing RE share percentages have lower levels of CO_2 emissions?

Figure 3 shows the percentage breakup of CO_2 emissions from combustion (a), manufacturing and construction (b), buildings (c) and transport (d) for the period between 1990 to 2015. For most countries the median CO_2 emission is higher from combustion and use of transport and much lower in case of manufacturing and building construction.

As the last few decades have seen immense development and economic progress globally, it came at a high cost environmentally. The various developmental activities like construction, use of transport and combustion

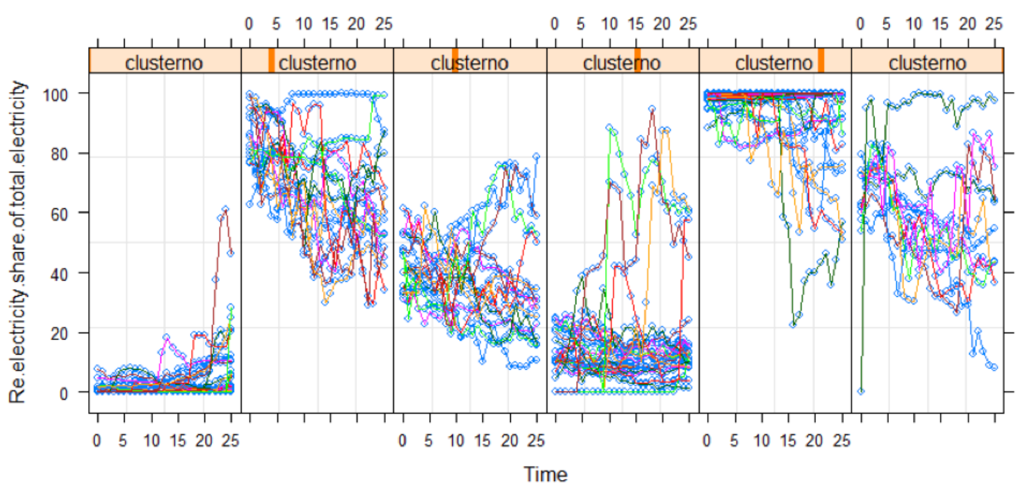


Figure 3: The figure depicts the six homogeneous clusters based on the predicted trend of RE share over time

Table 4: Countries grouped by the homogeneity in their effects of time on RE share of total energy

Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5	Cluster 6
Saudi Arabia	Benin	Guatemala	Dominica	Indonesia	Democratic Republic of the Congo
Brunei Darussalam	Tonga	El Salvador	Nicaragua	China	Ethiopia
Botswana	Kiribati	Angola	Papua New Guinea	India	Republic of the Congo
United Arab Emirates	Jamaica	Kenya	Zimbabwe	Mexico	Ghana
Marshall Islands	Netherlands	Tanzania	Myanmar	Burkina Faso	Lao PDR
South Sudan	Senegal	Honduras	Guinea	Equatorial Guinea	Paraguay
Trinidad and Tobago	Cape Verde	Central Africa	Thailand Sierra Leonne	Madagaskar	
Maldives	Vanuatu	Sri Lanka	Bangladesh	Suriname	Gabon
Niger	United Kingdom	Mozambique	Cuba	Belize	Venezuela
Antigua and Barbuda	Tuvalu	Mauritius	United States	Brazil	Vietnam
Micronesia	Cambodia	Nigeria	Mauritiana	Malawi	Mali
Algeria	Ecuador	Argentina	Australia	Rwanda	Chile
Guyana	Fiji	Philippines	Japan	Burundi	Sudan
South Africa	New Zealand	St. Vincent and the Grenadines	France	Cameroon	Haiti
Solomon Islands	Colombia	Samoa	Malaysia	Costa Rica	Togo
Seychelles	Panama	Sao Tome and Principe	Dominican Republic	Zambia	Namibia
St. Kitts and Nevis	Peru	Bolivia	Egypt	Uganda	

have all increased manifold due to the increase in population around the globe. And in turn they have increased the CO_2 emissions; the list of top countries who are high emitters contains developed as well as developing nations. Thus as a remedy to the increased environmental hazard, the use of clean energy is one of the foremost sustainable development goals. It is also evident from Figure 1 that some of the countries like China, Nigeria, and India show a higher level of RE share of the total energy consumption between 1990 and 2015. Correspondingly we can see that these three countries have a considerably low CO_2 emissions.

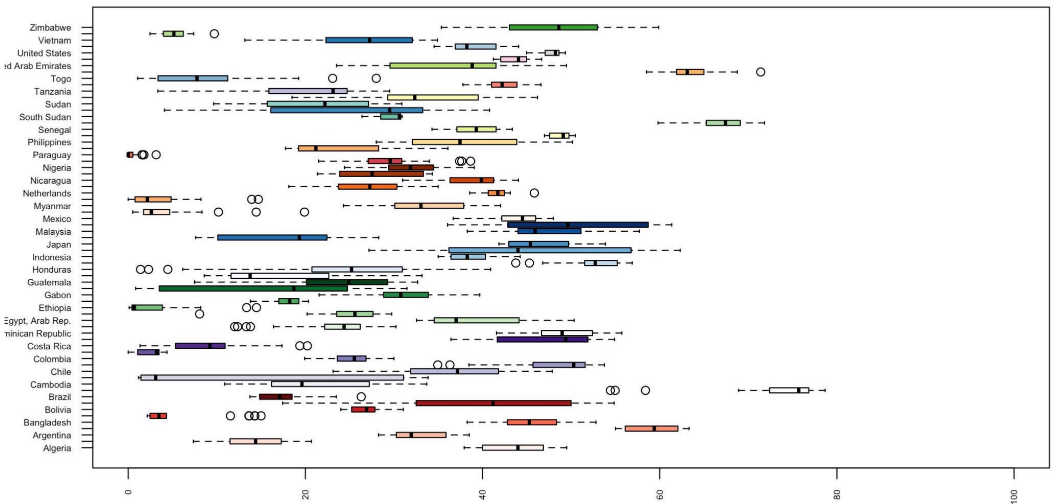
Figure 4 shows that the trend over time of CO_2 emission for select countries as exemplars. The varying trend in slope and the intercept called for a random slope and intercept in the mixed effects model. In case of Bangladesh, India and Malaysia we can see a general upward trend, however, there are variations at the micro-level between the years. And in case of Nigeria, we see a different pattern of increase till year 2004 and decrease thereafter. Also we can see in Figure 5, there is a potential structural change in RE share over time, which led us to introduce the interaction term between RE share and time in the model to predict CO_2 emission.

The model specifically used for studying the effect of RE share and time on CO_2 emissions over the years 1990 to 2015 takes the following form;

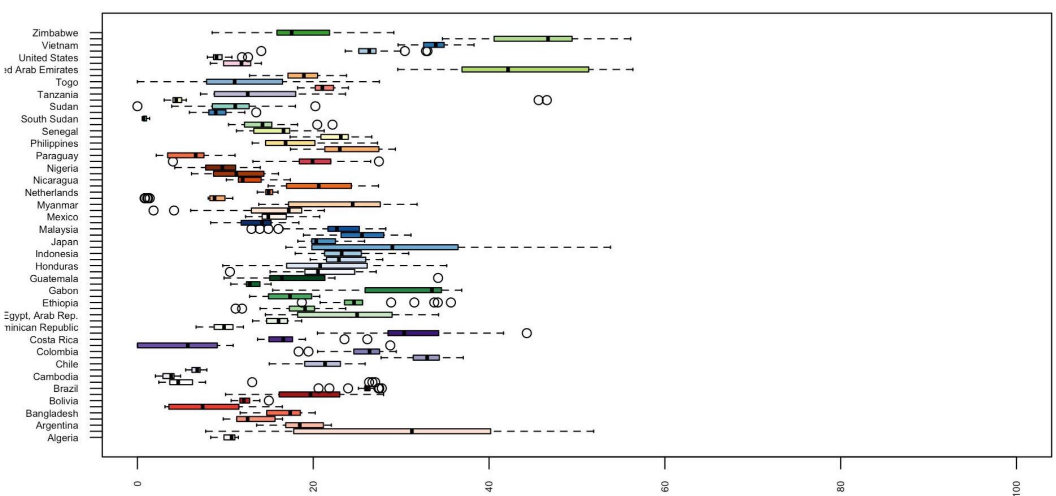
$$\text{CO}_{2ij} = (\alpha_0 + v_{i0}) + (\alpha_1 + v_{i1})\text{Year}_{ij} + +\alpha_2 \text{RE share}_{ij} + \alpha_3 \text{RE share}_{ij} \times \text{Year}_{ij} + e_{ij}$$

where CO_{2ij} is the CO_2 emission for the i^{th} country in the j^{th} year, α_0, α_1, α_2 and α_3 are fixed effects parameters. Results for the fixed effects from the country-specific model are given in Table 5.

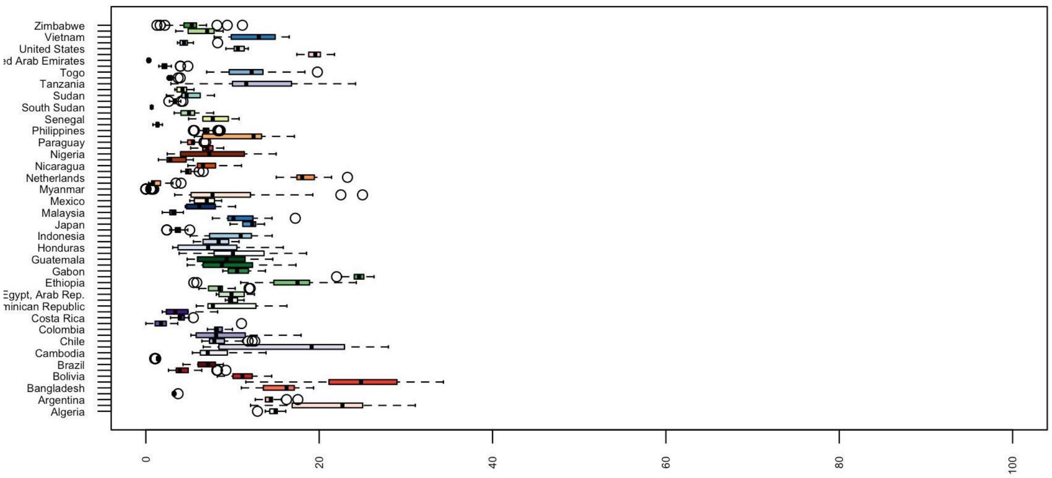
The results suggest significant evidence for approximately 4% annual average global increase in CO_2 emission over time. There are numerous reasons that can explain this increase. In developed countries like the United Kingdom, major sources of CO_2 emission are the use of motor vehicles for transport and manufacturing;



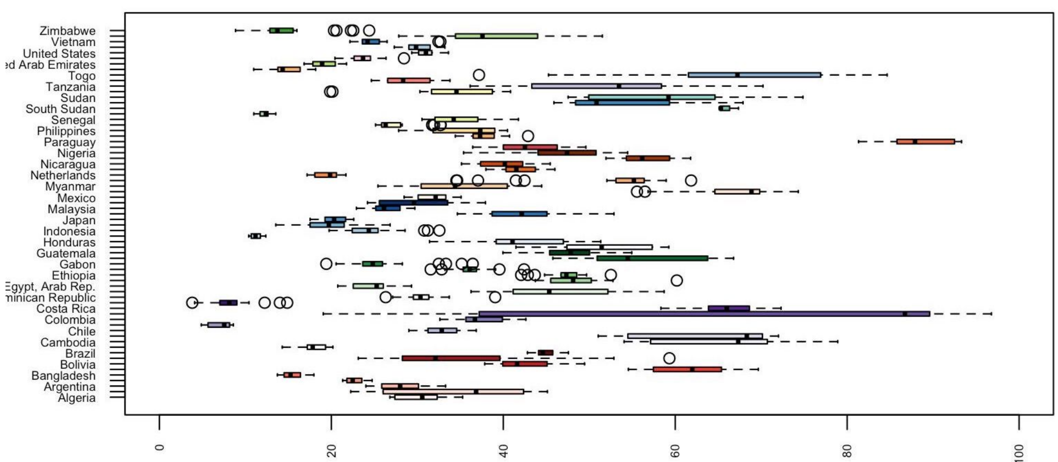
(a) Combustion



(b) Manufacturing



(c) Buildings & construction



(d) Transport

Figure 3: Country-specific box-plots for amount of CO_2 emission from different sources: (a) Combustion (b) Manufacturing (c) Buildings & construction (d) Transport

this can be seen from Figure 3 (d). In developing countries like Uganda, combustion and construction activities in pursuit of development is a major contributor to increased CO_2 emission; this is as shown in figures 3 (a) and (b). However, when we examine the impact of increased RE share over CO_2 emission, we find the coefficient to be negative. Thus, increased use of renewable energy is associated with a decrease in CO_2 emission.

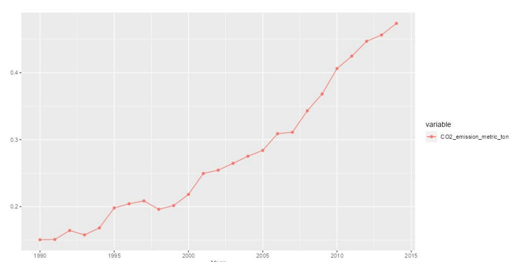
The interaction term between RE share and time also has a (significant) negative coefficient, indicating that although there is an increasing trend in CO_2 emission over time, the magnitude is reduced for countries which have invested in increasing the RE contribution to total energy.

5.3 Has access to clean energy changed adequately over time?

On average, 72.8% of the urban population and 39.2% of the rural population of a country had access to clean energy at baseline. The average rate of growth was 0.57% for urban and 0.94% for rural populations. Patterns in access are heterogeneous across countries and as before we cluster the subject specific coefficients from the model defined below reference? using PAM. Like the models for studying fixed and country-specific effects of time on RE share and CO_2 emission, we use the LMM for modeling access to clean energy for the rural and urban regions. The LMM is tweaked to model a bivariate regression of the form,

$$\text{Rural Access}_{ij} = (\gamma_0 + w_{1i0}) + (\gamma_1 + w_{1i1})\text{Year}_{ij} + e_{1ij}$$
$$\text{Urban Access}_{ij} = (\delta_0 + w_{2i0}) + (\delta_1 + w_{2i1})\text{Year}_{ij} + e_{2ij}$$

where Rural Access and Urban Access are respectively the percentages of rural and urban population with access to clean energy in the i^{th} country in the j^{th} year. Figure 6 shows that the trend in access to clean energy in the rural and urban areas of select countries. These countries represent the four different clusters created



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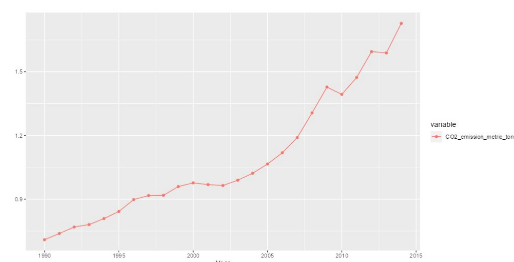

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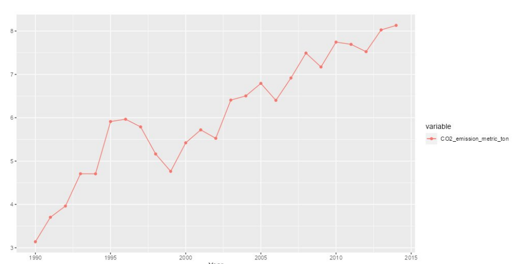

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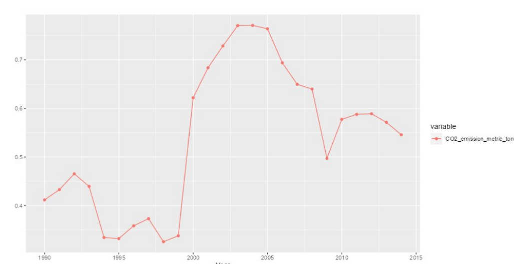


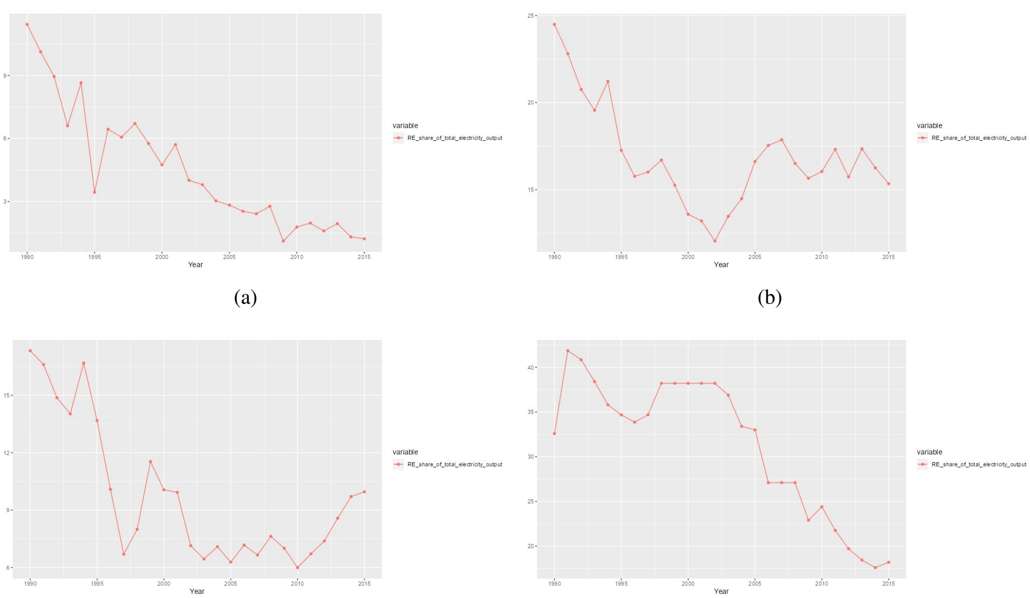
(h)

Figure 4: Country-specific trends for amount of CO_2 emission from different countries: (a) Bangladesh (b) India (c) Malaysia (d) Nigeria

based on homogeneity of the effect of time on access to clean energy. Due to the varying trend in slope and the intercept called for a random slope and intercept in the mixed effects model.

Table 6 presents the model coefficients corresponding to the independent variable *time* for each cluster which shows annual average rate of change in access to electricity over time. In the urban sector (table 6) we can see that cluster 2 (countries like Kenya, Cambodia, Niger, and Uganda) show the largest increase while cluster 4 (countries like Brazil, Chile, India and South Africa) shows maximum decrease in the access. However, the rural sectors (see table 6) of cluster 4 show an increase in yearly growth of access to clean energy, whereas for cluster 2 the there is a decrease. The results from Table 6 indicates that cluster 3 (countries like Bangladesh, Ethiopia, Ghana and Nigeria) have the highest yearly increase, suggesting improvement in access of the rural sectors of these countries. An annual decrease (-0.626) for cluster 1 (developed countries like the United States, the United Kingdom, France, Japan, and Netherlands) indicate a lower annual growth in access to clean energy in the rural sectors of these countries.

It is also interesting to note that there is a variation in the intercepts between the clusters, some of the intercept values are positive and some are negative. The intercept values in the table reflect the deviations of each cluster from the overall intercept from the fixed effects. In table 6 the baseline represents the cluster specific intercepts, where clusters 1,3 and 4 have a positive value, indicating that the expected access to clean energy at the first time point (i.e. 1990) for these clusters is more than that of the overall intercept for all the ISA member nations. Whereas, in case of cluster 2, the baseline intercept is much lower than the fixed effects



(a) (b) (c) (d)

Figure 5: Country-specific trends for amount of RE share from different countries: (a) Bangladesh (b) India (c) Malaysia (d) Nigeria

Table 5: Estimated fixed effects coefficients from subject specific regression model of CO_2 on RE share and time.

Term	Estimate	Std. error	p-value
Intercept	7.137^{***}	1.865	0.0001
RE share	-1.176^{**}	0.381	0.002
Year	0.037^{***}	0.009	0.0001
RE share $\times$ Year	-0.0001^{**}	0.0002	0.001

intercept. Thus, for countries in cluster 2 (countries like Kenya, Cambodia, Niger, and Uganda) the baseline values of access to clean energy is much lower. In table 6 we can see a slightly different pattern. The rural locations of both clusters 2 ans 3 have a lower baseline value of access. But they are higher for the rural locations of clusters 1 and 4. Hence, comparing across urban locations, countries in clusters 1, 3 and 4 have better than average access to clean energy, but for rural locations only clusters 1 and 4 provide better access to clean energy than the average.

The countries in each cluster are listed in the Table 7.

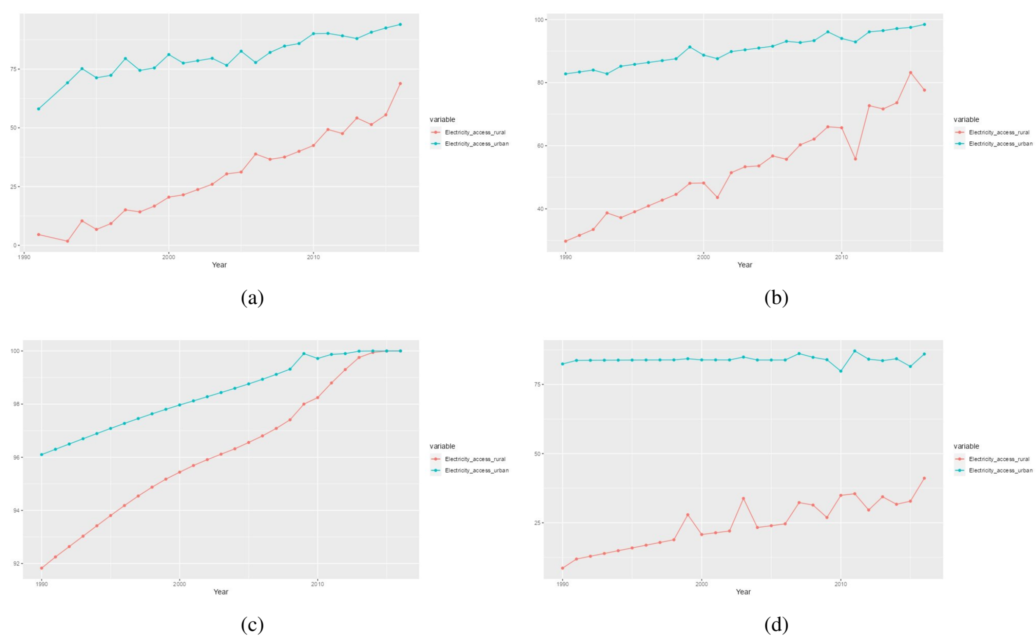


Figure 6: Trends in access to clean energy in rural and urban areas of different countries: (a) Bangladesh (b) India (c) Malaysia (d) Nigeria

Table 6: Deviations from average by cluster

	Urban		Rural		
Cluster no.	Average baseline access (Intercept)	Annual change	Average baseline access (Intercept)	Annual change	Characterisation
Cluster 1	28.415	−0.608	53.975	−0.626	High baseline but steady decrease
Cluster 2	−50.888	1.116	−35.615	−0.538	Low baseline and increase (urban) Low baseline but decrease (rural)
Cluster 3	4.865	−0.209	−33.295	0.674	Moderate baseline but decreasing (urban) Low baseline and increasing (rural)
Cluster 4	17.609	−0.299	14.936	0.491	Moderate baseline but decreasing (urban) Moderate baseline and increasing (rural)

6 Conclusion

The purpose of carrying out this study was to explore the trends and inter-linkages between CO_2 emission and RE share of total energy between 1990 and 2015. Four research questions were posited at the onset of this study, which we have tried to answer based on the data from ISA member nations. From our empirical results we have found that, RE share increases over time on average for all the countries; similar trends have also been presented in other studies for both developing and developed nations (Bilgen et al. (2004)). But it has also been shown that there are some limitations to this growth as well (Hansen et al. (2017)). The country specific analysis in our study lead to the identification of six distinct clusters of countries. There are 121 members in the ISA, and while studying the RE pattern through visualisation, it was important that a country-specific study was carried out to understand the varied nature of the trend. Although, the overall fixed effects show an increasing trend in RE share, the heterogeneity in the socio-economic conditions in these countries call for a mixed effects model to study the country specific effects as well. And from our empirical findings, distinct clusters of countries emerge, with similar pattern in RE consumption over time. The heterogeneity in pattern is depicted in Figure 3. The results from these country-specific studies help understand the effectiveness of policies undertaken by the countries. For instance, in case of New Zealand the *Projects* scheme undertaken to promote RE usage is completely voluntary and due to a lack of strict target has failed to improve RE over the years; thus New Zealand has been grouped into cluster 2 where a stagnant or decreasing trend is seen in RE share over the years (Kelly (2007)). But in case of Australia, the implementation of the Mandatory Renewable Energy Target (MRET) relatively easily meets its objective (Kelly (2007)). Hence we find Australia in cluster 4 where a general trend for the countries in this group is to have a more or less stable RE generation which is much higher than the rest of the clusters. Thus, a temporal study of the RE share provides empirical findings that can help in policy implementation.

As outlined in the introduction, many nations in the recent times have undertaken the sustainable development goals with major focus on the increased use of RE. In this study we have explored the patterns of

Table 7: Clusters of nations grouped by their similarity in effects of time on access to clean energy.

Cluster 1: where the baseline access is high but shows a negative trend	Cluster 2: Low baseline access but increasing trend in urban area and decreasing trend in rural area	Cluster 3: moderate baseline access but decreasing trend in urban area and increasing trend in rural area	Cluster 4: moderate baseline access but decreasing trend in urban area increasing trend in rural area
Algeria	Angola	Bangladesh	Brazil
Antigua and Barbuda	Benin	Bolivia	Chile
Argentina	Botswana	Burundi	Dominica
Australia	Burkina Faso	Cameroon	Dominican Rep.
Belize	Cambodia	Cape Verde	El Salvadore
Brunei	Central African Rep. Congo	Ethiopia	Equatorial Guinea
Darussalam	Dem. Rep. Congo	Gabon	Fiji
China	Kenya	Ghana	Guatemala
Colombia	Madagascar	Haiti	Guyana
Costa Rica	Malawi	Kiribati	Honduras
Cuba	Mawi	Lao PDR	India
Ecuador	Mauritiana	Marshall Islands	Indonesia
Egypt	Mozambique	Micronesia	Jamaica
Arab Rep.	Niger	Myanmar	Maldives
France	Rwanda	Namibia	Nicaragua
Japan	Sierra Leone	Nigeria	Panama
Malaysia	South Sudan	Papua New Guinea	Paraguay
Mauritius	Tanzania	Peru	Phillipines
Mexico	Togo	Senegal	Sao Tome and Principe
Netherlands	Uganda	Solomon Islands	South Africa
New Zealand	Zambia	Sudan	Sri Lanka
Samoa		Vanuatu	St. Vincent and Grenadines
Saudi Arabia		Zimbabwe	Thailand
Seychelles			Vietnam
St. Kitts and Nevine			
Suriname			
Tonga			
Trinidad and Tobago			
Tuvalu			
United Arab Emirates			
United Kingdom			
United States			
Venezuela			

increasing or diminishing RE capacity of the ISA member countries. Based on the clusters created from the homogeneous pattern in RE share of total energy over time, we can see that some of the emerging economies in cluster 1, like Botswana, and South Sudan, the initial years had seen very little use of RE but there is an increasing pattern over the 25 years. Thus, with more economic development, there is increased focus on use of cleaner form of energy. Likewise if we look at cluster 4 countries like Zimbabwe, and Myanmar, the pattern of RE share trend over time is either stagnant with very few of them showing any improvement. This can be explained to some extent based on the hypothesis of Environmental Kuznet Curves, that although with increase in economic development, environmental pollution also increases, after a threshold of economic development there is initiatives to remediate the pollution. The ISA members who are listed as developing nations, a pattern can be seen that validates this hypothesis.

To find answer to research questions 1 and 3, first an exploratory analysis of the data on CO_2 emission depicted a stationary trend over the study time period. In other words the CO_2 revolves around its overall mean for all ISA member countries. This implies that CO_2 emission over the study period is relatively stable. However, from Figure 1 we can also see that while average CO_2 emission increases over time, increased use of RE is associated with reduced emissions. Especially, for countries like the United States and Australia, the sustainable development target 7.2 has been achieved to a large extent. Finally, we have looked into the access to clean energy in the rural and urban sectors of the nations. Having established that there is a general trend in increase in RE capacity in the member countries, it was important to look into the access of the clean energy from RE sources to the rural and urban sections of the country. We studied the access of clean energy specific to the various countries; for a deeper understanding we have also separately looked at clean energy access for the rural and urban sectors. The two sectors presented starkly varied time trend, with almost twice as large a percentage of the urban population having access to clean energy than the rural. But the rural sector also showed promise in increasing the percentage of population with access to clean energy at a bigger rate than the urban. Thus, currently many of the ISA members nations like Zambia and Mozambique have shown significant annual increase in access to clean energy in the urban areas. And in countries Ghana, Nigeria, Zimbabwe, and Brazil a significant increase is seen in access in the rural areas. These are encouraging findings that address sustainable development target 7.1 of universal access to affordable and clean energy.

Further directions for research can include causal modelling to explore whether the association between the rate of change in emissions and the percentage of energy contributed by renewable sources can be assumed to be causal. While causal models have been explored for select small groups of countries, the challenge would be to incorporate the heterogeneity across countries into the model. An additional direction of interest would be to relate the joint variation in access, emissions and renewable energy percentages to country specific socioeconomic factors.

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