The underlying trend of OPEC energy intensity and the environmental implications

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Abstract

Given the upward trend of OPEC energy intensity, policymakers need a good understanding of the underlying factors and the environmental impacts when considering future energy policies. An index decomposition analysis is used to decompose OPEC energy intensity covering 1971–2017. The link between the decomposed energy indices and CO2 emissions is examined using structural time series and least square dummy variable corrected models. Both models also estimate the underlying carbon emission trend (UCET) which arguably reflects the impact of non-economic factors. For OPEC as a group, increases in energy intensity are linked to both energy inefficiency and structural shifts towards energy-intensive activities. About 62 per cent of the increases are attributed to the former, and the remaining 38 per cent is due to the later. The country-level results also show major contributions from both components to energy intensity. The econometric results show that shifts towards energy-intensive activities and, notably, deteriorating energy efficiency generally go in tandem with substantial increases in CO2 emissions. The estimated UCET is upward sloping indicating carbon-emitting behaviour, taste and lifestyle. Therefore, policies aimed at conserving energy and limiting the concentration of energy-intensive activities in the oil-exporting countries should be considered alongside other policies that attempt to influence behaviours and lifestyles.

1. Introduction

OPEC energy intensity, defined as its total energy consumption over real GDP (a tonne of oil equivalent per thousand 2010$US), increased almost threefold from 0.078 in 1971 to 0.203 in 2017 and diverged from the world energy intensity, which steadily declined from 1971. Arguably, this does not represent sustainable energy consumption. Figure 1 compares the trend of OPEC and the world energy intensity from 1971 to 2017. Energy JEL classification: C22, Q41, Q43.
intensity declined at an average annual rate of 1.177 per cent for the world while it increased at an average annual rate of 1.94 per cent for OPEC. Given the foregoing and considering that about 7.03 per cent of world energy use in 2017 is linked to OPEC, it is clear that changing OPEC energy intensity trajectory would enhance global energy sustainability and reduce future global CO₂ emissions.

The rapid increase in the OPEC energy intensity cannot be attributed solely to its failing energy efficiency; there are good reasons to believe that the structural changes that have occurred in some OPEC countries are contributing factors. Although none of OPEC countries is yet to be regarded as developed countries, OPEC members, in general, have used the revenue generated from the oil sector to transform other sectors, modernise and industrialise their economies, thereby increasing energy consumption. Besides, the artificially low energy prices through the wide variety of energy subsidies in OPEC countries may catalyse both failing energy efficiency (Olivia and Gibson, 2008; Fattouh and El-Katiri, 2013) and lowering costs of energy-related inputs for production, thus stimulating structural shifts towards energy-intensive activities.

Knowing this fact, the question that arises is what drives OPEC energy intensity and the environmental implications? To answer this question, there is a need to understand better the underlying trends of OPEC energy intensity and their links to the environment.

Figure 1 The historical trend of energy intensity from 1971 to 2017. [Colour figure can be viewed at wileyonlinelibrary.com]
To do this, we decompose changes in OPEC energy intensity into contributions due to structural shifts in economic activities and changes in energy (in)efficiency; then, we analyse the impacts of the decomposed components on the environment. With this, policymakers can consider the most appropriate policies to influence OPEC energy intensity trajectory for a more sustainable and environmentally friendly energy consumption path.

Many previous attempts have decomposed energy intensity (e.g. Boyd et al., 1987; Gardner, 1993; Boyd and Roop, 2004; Huntington, 2010; Zhao et al., 2010; Mulder, 2015). A separate strand of the literature also decomposed energy intensity as well as examined the underlying determinants (e.g. Metcalf, 2008; Oseni, 2011; Jimenez and Mercado, 2014; Moshiri and Duah, 2016). More recently, a study by Tajudeen et al. (2018) separated energy efficiency from energy intensity and provided a modelling framework for estimating the relationship between energy efficiency and CO₂ emission at the macro-level.

Despite the rapid rise in energy intensity for OPEC countries, most of the studies that assessed changes in energy conservation/efficiency have either focused on OECD or other developed countries. Only a few studies have focused on OPEC countries but have mostly investigated the link between energy consumption and economic growth (e.g. Squalli, 2007; Hossein et al., 2012). Sari and Soytas (2009) examined the link between CO₂ emission, energy use and economic growth for five selected OPEC countries. The authors, however, emphasised that their study’s results might be unable to account properly for the recent trends in CO₂ emissions for the five countries or OPEC in general. A few other studies that examined similar links and focused on the Middle East and North African (MENA) countries have about six OPEC members, which are mainly the same as the five countries studied in Sari and Soytas (2009). A few studies have also focused on individual OPEC countries in a time series model. Nonetheless, either in a panel or in time series setting, yet there is no study for the entire OPEC members. Therefore, policymakers in OPEC countries are left only with the option of relying directly on estimates from developed countries. Arguably, this may lead to inappropriate policy actions because most OPEC countries do not possess the same characteristics as developed countries. As noted by Adetutu (2014) also, alongside the ongoing international negotiations on climate change policy, adequate and reliable information on energy efficiency trends in developing countries, of which OPEC constitutes an important part, is required.

On its part, none of OPEC’s members belongs to Annex I countries with mandatory emission reduction targets under the Kyoto Protocol. OPEC opposed the full implementation of the protocol because it would reduce the demand for oil and slow down growth in their revenues from oil exports. It has also argued for compensation for any loss in oil revenue (Barnett et al., 2004). However, OPEC soon realised that the
devastating impact of global warming did not respect national borders or exempt any country. In fact, due to the relatively low renewable freshwater resources and the intense desertification problems in some OPEC countries, many OPEC members may be among the most susceptible in the face of increasing atmospheric temperatures (Sari and Soytas, 2009). OPEC members now acknowledge that environmental issues need to be addressed and have found it worthwhile to create and support the development of technologies, activities and policies to mitigate future climate change. Specifically, all the 14 OPEC members have signed the Paris Agreement on the reduction of climate change and four of them have already ratified it. The findings from this study, therefore, will be instructive for policymakers in the OPEC countries and other related countries.

This study adopts similar procedure in Tajudeen et al. (2018) and, as far as we know, is the first empirical study to decompose OPEC energy intensity into two key components and examine their impact on the environment. Firstly, it uses an index decomposition analysis (IDA) based on the Fisher Ideal Index to decompose OPEC’s energy intensity index into an energy efficiency index and a structural shift index. Next, it uses structural time series and bias-corrected least square variable models to examine the impacts of the IDA-based energy (in)efficiency and structural shift indices on CO₂ emissions while also controlling for other key economic and ‘exogenous non-economic’ factors such as lifestyles, tastes and values. Note that in this paper, improving and deteriorating energy efficiencies are used interchangeable as energy efficiency and inefficiency, respectively.

On the one hand, this study, which covers the 14 OPEC member countries as of 2018 and extends its analysis to the environment, is an attempt to improve on Adetutu (2014) that employed a modified translog cost function to estimate energy (in)efficiency and account for the energy–capital substitutability for four OPEC countries. On the other hand, given that Tajudeen et al. (2018) focused on OECD countries and found that they generally experienced improvements in energy efficiency, the application of the procedure to the OPEC countries, which have been generally deteriorating in energy efficiency, will help to build a complete body of evidence on the environmental implications of the changes (i.e. rise and fall) in energy efficiency. Moreover, this study will help provide insight on whether the magnitude of environmental impacts of energy efficiency improvement and the counterpart deterioration in energy efficiency are the same or not (i.e. symmetry or asymmetry).

The rest of this paper is structured as follows. Section 2 presents the research methodology with a brief description of the data. The empirical results are presented in section 3. Finally, section 4 offers concluding remarks with policy implications.
2. Methodology

This section gives details of the estimation method which follows the procedure in Tajudeen et al. (2018). The method combines a decomposition analysis (Metcalf, 2008) to separate energy intensity into energy (in)efficiency index and structural shift index, and econometric models (i.e. time series and panel data) to analyse the relationship between the decomposed indices and the environment (Ang, 2007) controlling for other key factors.

2.1. Energy intensity decomposition analysis

The index decomposition analysis (IDA) can be applied to data available at any level of aggregation or/and in time series format often used for decomposition analysis. Moreover, the Fisher Ideal Index (FII) and Logarithmic Average Divisia Index (LMDI) are preferred among the IDA-based methods. This is mainly due to their desirable properties such as ability to give exact decomposition without unexplained residuals, consistency in aggregation and satisfying the basic index theory properties such as the time-reversal and proportionality (Boyd and Roop, 2004). In this paper, we use the Fisher Ideal Index (FII) in applying the IDA.

The method presents aggregate energy intensity ($e_t$) as a function of sector-specific energy efficiency ($e_{jt}$) and structural activity ($s_{jt}$) as:

$$
e_t = \frac{E_t}{Y_t} = \sum_j \left( \frac{E_{jt}}{Y_{jt}} \right) \left( \frac{Y_{jt}}{Y_t} \right) = \sum_j e_{jt} s_{jt}, \quad (1)$$

where $E_t$ and $Y_t$ denote the total energy consumption and output, respectively; $E_{jt}$ and $Y_{jt}$ are the total energy use and economic output for sector $j$ in year $t$, respectively. The energy intensity index ($I_t$) is then constructed by dividing the energy intensity in year $t$ ($e_t$) by the energy intensity in a base year ($e_0$) as follows:

$$I_t = \frac{e_t}{e_0} = \frac{\sum_j e_{jt} s_{jt}}{\sum_j e_{j0} s_{j0}}. \quad (2)$$

Following Diewert (2001), if we can distinguish sectors that account for all of the energy consumption in the economy (without overlap) and there exists a set of economic activities measures $Y_{jt}$ with which to create a measure of sectoral energy intensity, the energy intensity index (equation (2)) can be decomposed into efficiency ($D_t^{EF}$) and activity ($D_t^{ACT}$) indices.5
\[ I_t = \frac{e_t}{e_0} = D_t^{\text{EF}}(e_{j0}, e_{jt}, s_{j0}, s_{jt}) \times D_t^{\text{ACT}}(e_{j0}, e_{jt}, s_{j0}, s_{jt}) \]  

(3)

To arrive at equation (3), the Laspeyres index and Paasche index that use a base period fixed weight and end period fixed weight, respectively, given below can be used.

Laspeyres:
\[ L_t^{\text{EF}} = \frac{\sum_j e_{jt}s_{j0}}{\sum_j e_{j0}s_{j0}}; \quad L_t^{\text{ACT}} = \frac{\sum_j e_{j0}s_{jt}}{\sum_j e_{j0}s_{j0}} \]  

(4)

Paasche:
\[ P_t^{\text{EF}} = \frac{\sum_j e_{jt}s_{jt}}{\sum_j e_{j0}s_{jt}}; \quad P_t^{\text{ACT}} = \frac{\sum_j e_{jt}s_{jt}}{\sum_j e_{j0}s_{j0}} \]  

(5)

However, these two indices might give residual terms which could account for a considerable degree of the variability in the underlying index of energy intensity and/or produce different decompositions results (Metcalf, 2008; Moshiri and Duah, 2016). The FII combines the weighted average of the Laspeyres and Paasche indices to help overcome these setbacks by decomposing the energy intensity perfectly into the two elements \( D_t^{\text{EF}} \) and \( D_t^{\text{ACT}} \) with no unexplained residuals. The FII efficiency index \( D_t^{\text{EF}} \) and activity index \( D_t^{\text{ACT}} \) are as follows:

\[ D_t^{\text{EF}} = \sqrt{\left( L_t^{\text{EF}} \times P_t^{\text{EF}} \right)}; \quad D_t^{\text{ACT}} = \sqrt{\left( L_t^{\text{ACT}} \times P_t^{\text{ACT}} \right)} \]  

(6)

And the aggregate energy intensity index is written as a product of the two indices as:

\[ I_t = \frac{e_t}{e_0} = D_t^{\text{EF}}(e_{j0}, e_{jt}, s_{j0}, s_{jt}) \times D_t^{\text{ACT}}(e_{j0}, e_{jt}, s_{j0}, s_{jt}) \]  

(7)

Using equation (7) and denoting energy savings (\( \Delta ESS_t \)) due to changes in energy intensity as \( \Delta ESS_t = E_t - E \), we can also separate changes in energy savings resulting from changes in energy efficiency and structural shifts in economy compositions as:

\[ \Delta ESS_t = \Delta ESS_t^{\text{EF}} \left( \frac{\ln(D_t^{\text{EF}})}{\ln(I_t)} \right) + \Delta ESS_t^{\text{ACT}} \left( \frac{\ln(D_t^{\text{ACT}})}{\ln(I_t)} \right) = \Delta ESS_t^{\text{EF}} + \Delta ESS_t^{\text{ACT}} \]  

(8)

where \( E_t \) is actual energy use and \( E \) is the energy that would have been used had energy intensity remained at a base-year level.

Due to data limitations, in particular, the lack of consistent sectoral income data, many studies that have applied this method are constrained to use just a few sectors. For example, Metcalf (2008) and Oseni (2011) decomposed energy intensity using four sectors for 46 US states and 16 OECD countries, respectively, and Moshiri and Duah...
(2016) decomposed energy intensity using seven sectors for 10 Canadian provinces. Having faced similar data constraint, this study attempts to decompose energy intensity using seven key sectors—manufacturing, mining, transport, construction, agriculture, commercial and residential sectors.

2.2. The econometric model of the decomposed energy intensity indices and the environment
In analysing the links between the decomposed energy intensity indices and the environment, this study follows Ang (2007) which combines the environmental Kuznets curve (EKC) and energy-income hypothesis to achieve a multivariate (3E) time series model given as:

$$CO_2_t = \phi_0 + \alpha_0 Y_t + \alpha_1 Y_t^2 + \alpha_2 E_t + \epsilon_t,$$

where $CO_2_t$ is CO2 emission per capita; $Y_t$ and $E_t$ are income and energy use per capita, respectively; $Y_t^2$ is the square of income per capita; and $\epsilon_t$ is the error term. $\alpha_1$ and $\alpha_2$ in equation (9) are used to test for the EKC hypothesis, and if the hypothesis holds, interpretations are given in terms of efficiency and structural composition impacts without actually providing estimates for these components. Increases in income would only necessarily translate to the improved environment if channelled to improve energy efficiency or spent on more environmentally friendly energy sources. Tajudeen et al. (2018) argued that a better approach to estimating the effects of these components on the environment would be to get the measure of actual energy input per useful output of energy (i.e. the true (in)efficiency) and structural composition of the economy. We could then examine the impacts on CO2 emissions rather than relying on the income and its threshold as captured by $\alpha_1$ and $\alpha_2$ in equation (9). This study adopts Tajudeen et al. procedure by replacing $E_t$ in equation (9) with the drivers such as energy efficiency and structural shift (Adetutu et al., 2016) to arrive at a multivariate model as:

$$CO_2_t = \phi_0 + \alpha_0 Y_t + \beta_0 EF_t + \gamma_0 EF_t^2 + \varphi_0 ACT_t + \Phi_0 ACT_t^2 + \psi_0 ES_t + \omega_0 TO_t + \epsilon_t,$$

where $EF_t$ is proxied by the energy efficiency index derived from the decomposition analysis.

To avoid omission bias, equation (10) controls for cleaner energy substitute and the openness of the economy to trade captured by $ES_t$ and $TO_t$, respectively. The relationship between CO2 emissions and energy (in)efficiency is also assumed to be nonlinear by adding the squared term of the efficiency index $EF_t^2$ in the model. This is essential since countries that are energy inefficient may improve over time and become
energy efficient, hence, reductions in CO2 emissions. It follows that if a country is having a declining energy efficiency index and we found \( \beta_0 > 0 \) and \( \gamma_0 < 0 \) in equation (10), then energy efficiency forms a U-shape link with CO2 emissions after a given minimum. In contrast, if the country is having an increased energy efficiency and we found \( \beta_0 > 0 \) and \( \gamma_0 < 0 \) in equation (10), then the nonlinear effect forms an inverted U shape after a given threshold. There could also be a declining return to improving energy efficiency (in terms of marginal reductions in CO2 emissions over time), which would mean a nonlinear effect. A similar analogy is used to include the square of structural shift index \( ACT_t^2 \) in the model.\(^7\)

Considering that CO2 emissions may not adjust immediately to change in energy efficiency or any other variables in the model and the previous level of CO2 emissions may instigate stringent policy to mitigate future CO2 emissions, we adjust equation (10) to a dynamic model, starting with lags of 2 years of all of the variables. Lastly, in addition to changes in energy efficiency and technological progress (or regress), the emphasis that exogenous non-economic factor (ExNEF) such as societal preferences, lifestyle, attitudes and environmental awareness may have a significant impact on CO2 emissions is considered by introducing an underlying carbon emissions trend \( UCET \) in the model. The UCET is unobservable and could be stochastic or deterministic and is assumed to be influenced mainly by the ExNEF.

Putting all these factors together, the final model to be estimated is as follows:

\[
\lambda(L)CO_2 = \mu_t + \alpha(L)y_t + \beta(L)ef_t + \gamma(L)ef_t^2 + \phi(L)act_t + \Phi(L)act_t^2 + \psi(L)ES_t + \omega(L)TO_t + \epsilon_t,
\]

where \( \lambda(L) \), \( \alpha(L) \), \( \beta(L) \), \( \gamma(L) \), \( \phi(L) \), \( \psi(L) \) and \( \omega(L) \) are polynomial lag operators equal to \( 1-\lambda_2L, 1+\alpha_1L+\alpha_2L, 1+\beta_1L+\beta_2L, 1+\gamma_1L+\gamma_2L, 1+\phi_1L+\phi_2L, 1+\Phi_1L+\Phi_2L, 1+\psi_1L+\psi_2L \) and \( 1+\omega_1L+\omega_2L \), respectively; other variables are as defined in equation (10). All variables except cleaner energy substitution and trade openness, which are in percentages, are in natural logs.\(^8\)

With equation (11), the short- and long-run elasticities of the regressors with respect to CO2 emissions can be estimated simultaneously.\(^9\) However, the inclusion of \( \mu_t \) in the model will render estimators such as OLS biased and inconsistent if \( \mu_t \) is stochastic. The structural time series model (STSM) by Harvey (1989) helps to overcome this problem and can be combined with an ARDL model. The order of integration of the variables is not very crucial for STSM and allows the trend component \( \mu_t \) in a regression model to vary stochastically over time. With STSM, \( \mu_t \) is assumed to have the following stochastic process:

\[
\mu_t = \mu_{t-1} + \epsilon_{t-1} + \eta_t \sim NID(0, \sigma_\eta^2)
\]

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\[ q_t = q_{t-1} + \xi_t \quad \xi_t \sim \text{NID}(0, \sigma^2_\xi) \]  

(13)

The trend includes a level (equation (12)) and a slope (equation (13)). \( \eta_t \) and \( \xi_t \) are random white noise disturbance terms. The nature of the trend depends on the restrictions imposed on the level, slope and the hyperparameters \( \sigma^2_\eta \) and \( \sigma^2_\xi \). At the extreme, if \( \sigma^2_\eta = \sigma^2_\xi = 0 \) is confirmed by a likelihood ratio (LR) test, the trend \( \mu_t \) collapses to a deterministic linear trend. Also, the inclusion of irregular, level and slope interventions in \( \mu_t \) gives information about possible breaks and structural changes at a period of the estimation (Harvey and Koopman, 1992).

### 2.3. Panel data model

Using similar exposition as in the time series model (equation (10)), we state the panel data model as.

\[
\text{CO}_2_{it} = \phi_0 + \alpha_0 y_{it} + \beta_0 \epsilon_{it} + \gamma_0 \epsilon_{it}^2 + \varphi_0 act_{it} + \varphi_0 act_{it}^2 + \psi_0 ES_{it} + \omega_0 TO_{it} + \theta_t D_t + u_{it}
\]

(14)

where \( i = 1, 2, \ldots, N \) represents each country in the panel; \( t = 1, 2, \ldots, T \) refers to the period and the composite error \( u_{it} = v_i + \epsilon_{it} \), where \( v_i \) is the unobservable country-specific effects; \( \epsilon_{it} \) is the idiosyncratic error term; and the definitions of other variables are as stated in equation (10). We include time dummies \( D_t \) to capture the impact of ExNEF in the panel data model (See, e.g., Griffin and Schulman, 2005; Adeyemi and Hunt, 2007).

Since \( \text{CO}_2_{it} \) is a function of \( v_i \), which is time-invariant, it follows that the inclusion of \( \text{CO}_2_{it-1} \) as an additional regressor would correlate with \( u_{it} \) which contains \( v_i \), rendering OLS biased and inconsistent. The least square dummy variable (LSDV) or random effects (RE) estimators do not completely solve this problem. A common solution is to take the first difference of equation (10) to eliminate \( v_i \) via either an instrumental variable Anderson and Hsiao (1982) or a generalised method of moments (GMM) estimator (Arellano and Bond, 1991). However, the basic properties of GMM estimators hold for small \( T \), large \( N \) panels. Consequently, the application of the GMM estimators to a small cross-section or large \( T \), as in our study, may bias the estimated parameters and standard errors.

Kiviet (1995) proposes an alternative method that directly corrects the bias of LSDV. The study uses dynamic panel data with \( T \leq 20 \) and \( N \leq 50 \) in a Monte Carlo analysis to show that the Anderson and Hsiao (1982) and Kiviet (1995) bias-corrected LSDV (LSDVC) estimator are better than the GMM estimator in this circumstance. Judson and Owen (1999) use a similar method to Kiviet to simulate data with qualities normally
encountered by macroeconomists, a large time dimension. Their results show that in a balanced long panel the LSDVC is the best option and Anderson and Hsiao’s approach performs well too.

With this exposition and the nature of our data—balanced panel with large T, small N, we use the LSDVC estimator to estimate the dynamic panel data model. We start to estimate the static model (equation (14)) using either FE or RE as applicable to serve as a benchmark for the dynamic model. Since the LSDVC is designed for a dynamic panel model with one lagged dependent variable, the dynamic model to be estimated is given as:

\[
\begin{align*}
\text{CO}_2_{it} &= \phi_0 + \alpha_0 y_{it} + \beta_0 e_{f_{it}} + \gamma_0 e_{act_{it}} + \Phi_0 e_{act_{it}^2} + \psi_0 E_{S_{it}} + \omega_0 T_{O_{it}} \\
&\quad + \theta_t D_t + \lambda_0 \text{CO}_2_{it-1} + u_{it}
\end{align*}
\]  

(15)

where \(\text{CO}_2_{it-1}\) is the first lag of \(\text{CO}_2\) emissions and other variables are as defined in equation (14).

We note that both equations (14) and (15) may be prone to other econometric issues including endogeneity and cross-section dependence, and we discuss and test for these issues in the result section. The panel data estimations are conducted using software package Stata 14.

2.4. Contributions of the different variables to changes in \(\text{CO}_2\) emissions

Following Broadstock and Hunt (2010), this subsection attempts to quantify the relative contributions of the drivers comprising energy (in)efficiency, structural shift, trade openness, cleaner energy substitution and exogenous non-economic factors to average annual growth in OPEC’s \(\text{CO}_2\) emissions using the estimated parsimonious model from equations (7) and (11). If the resulting parsimonious model does not have any lags, the contributions of the drivers are easy to derive. However, if the lagged terms in these models are significant, it is tedious to calculate the relative contributions to changes in \(\text{CO}_2\) emissions. In this situation, Tajudeen et al. (2018) suggest that the estimated long-run elasticities of the variables, which incorporate the lags in the estimated model, can be used alongside the changes in the corresponding variables to arrive at their relative contributions to changes in \(\text{CO}_2\) emissions. For the time series model, it is therefore specified as follows:

\[
\Delta \text{\text{CO}}_2_t = \Delta \hat{\mu}_t + \hat{\alpha}^* \Delta y_t + \hat{\beta}^* \Delta e_{f_t} + \hat{\Phi}^* \Delta e_{act_t} + \hat{\psi}^* \Delta E_{S_t} + \hat{\omega}^* \Delta T_{O_t},
\]  

(16)

where \(\hat{\alpha}^*, \hat{\beta}^*, \hat{\Phi}^*, \hat{\psi}^*\) and \(\hat{\omega}^*\) are the long-run elasticities of the corresponding variables. Thus, \(\hat{\alpha}^* \Delta y_t, \hat{\beta}^* \Delta e_{f_t}, \hat{\Phi}^* \Delta e_{act_t}, \hat{\psi}^* \Delta E_{S_t}, \hat{\omega}^* \Delta T_{O_t}\), and \(\Delta \hat{\mu}_t\) are the estimated relative contributions of income, energy (in) efficiency, structural shift, cleaner energy
substitution, trade openness and ExNEF, respectively, to the annual change in CO₂ emissions (ΔCO₂t).

For the panel data model, we use a similar method as in equation (16) and focus on the annual change in CO₂ emissions for OPEC as a group (ΔCO₂a). We use yt, efₜ, actₜ, ESₜ and TOₜ for OPEC as a group¹⁴ to substitute the country-level variables yt, efₜ, actₜ, ESₜ, and TOₜ, respectively, in equation (16). The panel data long-run elasticities from equation (15) are also used to replace the time series elasticities.

Lastly, using the method in Griffin and Schulman (2005), and Adeyemi and Hunt (2007), we derive the contribution from ExNEF from the expression Δðθt=1/C₀λ₀Þ, where ðθt=1/C₀λ₀Þ denotes the long-run estimated UCET, and θ and λ₀ are the coefficients of the time dummies and CO₂it-1, respectively, in equation (15).

2.5. Data description
The data set for the empirical estimation is annual data covering the period 1971–2017 for 14 OPEC countries¹⁵ comprising 658 observations in total. We present the definitions and sources of variables in Table 1.

For energy intensity decomposition analysis, we use data on aggregate and sectors economic output and energy demand. Aggregate output (AY) and energy demand (AE) are proxied by real GDP and total energy use, respectively. For sectors output (Yᵢ), we use the measure of economic output related to the underlying energy use by the seven energy-consuming sectors considered (i.e. mining, transport, manufacturing, construction, agriculture, commercial and residential). E.g., we prefer household consumption expenditure, a key driver of residential energy demand, to personal income as part of the later goes to savings, which may not have a major impact on residential energy demand. For the remaining six sectors, we use their value added (i.e. their contribution to the final output) as a proxy for economic output. We present the definitions and sources of variables in Table 1.

For the analysis of the decomposed energy indices and the environment, we use the energy (in)efficiency and structural shift indices derived from the energy intensity decomposition analysis, CO₂ emissions, income per capita and two control variables—alternative (renewable) energy as a percentage of total energy use (a proxy for cleaner energy substitution) and trade as a percentage of GDP (a proxy for trade openness). We present the summary statistics in Table A1 of the Appendix.

3. Empirical results
3.1. Empirical results of the decomposition of energy intensity
The results using the Fisher Ideal Index denoted by equation (7) to decompose the energy intensity index into efficiency and activity indices over the period 1971–2017 are illustrated in Fig. 2.¹⁶
Taking 1971 as the base year, the energy intensity index in 2017 for OPEC as a group is 232.67 per cent of its 1971 level (energy intensity index increases by 132.67 per cent between 1971 and 2017). The activity and efficiency indexes are 140.21 per cent and 165.94 per cent of the 1971 levels, respectively. That is, if energy efficiency had remained constant at its 1971 level for all sectors, energy intensity would have increased...
by 40.21 per cent. And, if the composition of the economic activity of OPEC countries as a group had remained constant at its 1971, energy intensity would have increased by 65.94 per cent.

Our findings show that the increasing intensity for OPEC as a group can be attributed to both structural shifts towards energy-intensive sectors and inefficient energy use. In all, 62.11 per cent of the rise in energy intensity between 1971 and 2017 is associated with the deterioration in energy efficiency while the remaining 37.89 per cent is associated with structural shifts towards energy-intensive sectors.

Using equation (8), we allocate the total energy dissaved (relative to the amount that would have been consumed had energy intensity remained at its 1971 level) between changes in energy efficiency and economic activity. Based on this method, roughly 50.94 per cent of total energy use (i.e. 444.88 million tonne of oil equivalent, Mtoe) is overuse due to the increase in OPEC energy intensity. The findings attribute 59.98 per cent of the energy overuse (~266.82Mtoe) to deteriorating energy efficiency and the remaining 40.02 per cent to changes in the composition of economic activity. The area graph depicted in Fig. 2 shows the trend of energy (dis)saving due to deteriorations in energy efficiency and compositional changes over the entire period. Initial increases in energy overuse can be attributed almost entirely to the former. By 1977, with a slight dominance from increasing energy inefficiency, the changing composition of economic activities now adds a significant portion of rising energy dissaving.

Figure 2 Energy indices and energy savings relative to 1971 for OPEC group-level. [Colour figure can be viewed at wileyonlinelibrary.com]
The decomposition results in Fig. 2 are at an aggregate level, deteriorating energy efficiency for OPEC as a group does not imply that all countries within the group are inefficient. A brief description of the decomposition results at the country level shows significant variations for the three energy indices across countries and across time.

The results for the three energy indices for the individual OPEC countries at various intervals between 1971 and 2017 are summarised in Table 2. Several facts are noteworthy. Energy intensity, efficiency and activity indices across countries have been increasing at averages of 5.88 per cent, 3.02 per cent and 1.39 per cent per annum, respectively, between 1971 and 2017. The increases were more rapid in the 1970s to 1980s but there were declines in energy intensity and efficiency indices in the 1990s. Also, variations in the indices across countries are rising.

Coefficients of variation for energy intensity, efficiency and activity indices increased by 76 per cent, 83 per cent and 91 per cent, respectively, across the individual OPEC countries between 1971 and 2017. This indicates that some countries may have increased their energy intensity due to deterioration in energy efficiency while other

| Indexes | Year          | Mean  | S.D. | Min  | Max  | COV   | Average annual change (%) | Average annual change (cumulative) |
|---------|---------------|-------|------|------|------|-------|---------------------------|-----------------------------------|
| Intensity | 1971–1982     | 1.341 | 0.727| 0.537| 5.401| 0.542 | 11.208                    | 11.208                            |
|          | 1983–1994     | 2.855 | 1.956| 0.526| 6.941| 0.685 | 7.988                     | 9.528                             |
|          | 1995–2006     | 2.963 | 2.058| 0.411| 8.340| 0.695 | −3.302                    | 5.129                             |
|          | 2007–2017     | 3.333 | 3.178| 0.589| 22.683| 0.954 | 8.270                     | 5.880                             |
|          | Total         | 2.608 | 2.262| 0.411| 22.683| 0.867 | 5.880                     | −                                 |
| Efficiency | 1971–1982    | 1.246 | 0.636| 0.639| 4.920| 0.510 | 7.537                     | 7.537                             |
|          | 1983–1994     | 2.091 | 1.264| 0.529| 5.224| 0.605 | 4.060                     | 5.723                             |
|          | 1995–2006     | 2.123 | 1.455| 0.399| 6.016| 0.685 | −2.921                    | 2.759                             |
|          | 2007–2017     | 2.175 | 2.028| 0.552| 16.611| 0.933 | 3.832                    | 3.106                             |
|          | Total         | 1.903 | 1.468| 0.399| 16.611| 0.771 | 3.016                     | −                                 |
| Activity  | 1971–1982     | 1.095 | 0.363| 0.602| 3.229| 0.332 | 3.078                     | 3.078                             |
|          | 1983–1994     | 1.406 | 0.802| 0.487| 4.232| 0.571 | 0.630                     | 1.801                             |
|          | 1995–2006     | 1.494 | 0.944| 0.543| 4.989| 0.632 | 0.896                     | 1.490                             |
|          | 2007–2017     | 1.591 | 1.006| 0.401| 4.920| 0.633 | 1.055                    | 1.386                             |
|          | Total         | 1.392 | 0.833| 0.401| 4.989| 0.598 | 1.386                     | −                                 |

SD is standard deviation; Min and Max are minimum and maximum values, respectively; COV is the coefficient of variation
countries may not have. These variations, thus, buttress the need to further analyse the three indices at the individual country level.

3.2. Country-level results of the decomposed energy indices

Further decomposition results for the country level between 1971 and 2017 are presented in Table 3. Of the 14 OPEC countries considered as of 2018, 11 show an upward trend in energy intensity index, with Angola, Congo and Nigeria, showing a declining energy intensity index. In 2017, Angola is the only country in the group that achieved improvement in energy efficiency and a structural shift to less energy-intensive activities. However, the average annual (1971–2017) efficiency index of 143 per cent of its 1971 level shows that the previous deterioration in Angola’s efficiency index still dominates the recent improvement of the efficiency index achieved.

Specifically, in 2017 for 12 OPEC countries, shifts in economic activity contribute to the increases in their energy intensity. The exceptions are Angola and Congo where their activity indices being 95 per cent and 82 per cent of their 1971 levels, respectively. Thus, energy intensity for the two countries would have been 95 per cent and 82 per cent of their 1971 levels, respectively, had their energy efficiency index remained unchanged between 1971 and 2017. Similarly, only three OPEC countries (Angola, Ecuador and Nigeria) were found to have become more energy efficient; that is, their efficiency index in 2017 declined by 8 per cent, 14 per cent and 13 per cent, respectively, relative to their 1971 level. This is not surprising given that Angola, Ecuador and Nigeria are among the OPEC countries with the lowest energy self-sufficiency and the total primary energy supply per capita. Besides, these countries have relatively the highest energy (diesel and gasoline) prices among the OPEC countries. Thus, there are more compelling factors for industries and/or households in these countries to be energy efficient.

The average annual changes for the three indices are positive for 10 OPEC countries, ranging from 0.25 per cent (Ecuador) to 16.66 per cent (Saudi Arabia) for energy intensity. The average annual changes for efficiency and activity indices vary from 0.25 per cent (UAE) to 20.48 per cent (Libya) and 0.02 per cent (Nigeria) to 7.79 per cent (UAE), respectively. The exceptions are Angola, Nigeria and Gabon (with decline rates of 0.28 per cent, 0.28 per cent and 0.05 per cent, respectively, for the energy intensity); Angola and Congo (with decline rates of 0.11 per cent and 0.40 per cent, respectively, for the activity index); and, more importantly, Angola, Nigeria and Ecuador (with decline rates of 0.18 per cent, 0.29 per cent and 0.31 per cent, respectively, for the efficiency index).

The last three columns of Table 3 show the total energy (dis)saving and shares due to changes in energy efficiency and structural shift, using equation (8). Only Congo saved energy from both improved energy efficiency and structural shift. The largest average saving of 0.42 quads of energy is from Congo. IR Iran followed by Saudi Arabia has the
Table 3 Energy intensity index and decomposition results for OPEC country level

| Country   | Indexes values in 2017 (1971 = 1) | Indexes average Values: 1971–2017 | Indexes average annual change (%) | Indexes average energy savings (ΔESS) |
|-----------|----------------------------------|------------------------------------|-----------------------------------|--------------------------------------|
|           | EI  | Eff. | Act. | EI  | Eff. | Act. | EI  | Eff. | Act. | EI  | Eff. | Act. |
| Algeria   | 2.92| 2.48 | 1.18 | 2.30| 2.12| 1.08 | 4.18| 3.21| 0.39 | -12.87| -11.59| -1.28 |
| Angola    | 0.87| 0.92 | 0.95 | 1.16| 1.43| 0.86 | -0.28| -0.18| -0.11| -1.95 | -1.55 | 1.16 |
| Congo     | 0.98| 1.20 | 0.82 | 0.68| 0.75| 0.95 | -0.05| 0.43 | -0.40| 0.42 | 0.30 | 0.12 |
| Ecuador   | 1.11| 0.86 | 1.30 | 1.10| 0.96| 1.16 | 0.25 | -0.31| 0.65 | -0.77 | 0.48 | -1.24 |
| Gabon     | 1.98| 1.22 | 1.62 | 1.21| 1.06| 1.10 | 2.12 | 0.47 | 1.36 | -0.48 | -0.21| -0.28 |
| IR Iran   | 5.33| 2.13 | 2.50 | 3.72| 1.78| 1.99 | 9.42 | 2.46 | 3.27 | -71.89| -33.42| -38.47 |
| Iraq      | 1.64| 1.50 | 1.10 | 2.29| 1.80| 1.22 | 1.40 | 1.09 | 0.21 | -7.88 | -1.96 | -5.92 |
| Kuwait    | 3.09| 1.31 | 2.35 | 2.54| 1.27| 1.96 | 4.55 | 0.68 | 2.95 | -6.34 | -5.09 | -1.25 |
| Libya     | 13.68| 10.42| 1.31 | 4.32| 3.32| 1.26 | 27.5 | 20.48| 0.68 | -6.34 | -5.09 | -1.25 |
| Nigeria   | 0.87| 0.87 | 1.01 | 1.13| 1.17| 0.99 | -0.28| -0.29| 0.02 | -4.60 | -3.84 | -0.77 |
| Qatar     | 4.29| 3.87 | 1.11 | 4.73| 4.00| 1.16 | 7.16 | 6.23 | 0.24 | -8.33 | -7.63 | -0.70 |
| Saudi     | 8.66| 4.34 | 2.00 | 5.97| 4.14| 1.37 | 16.66| 7.27 | 2.16 | -58.20| -45.33| -12.88 |
| UAE       | 5.11| 1.11 | 4.58 | 4.11| 1.11| 3.65 | 8.93 | 0.25 | 7.79 | -18.50| -1.23 | -17.27 |
| Venezuela | 1.32| 1.21 | 1.09 | 1.25| 1.75| 0.74 | 0.69 | 0.45 | 0.20 | -8.72 | -19.96| 11.25 |
largest energy dissaving of 71.89 and 58.20 quads of energy, respectively. Further analysis of the energy intensity decomposition at the country level was conducted by estimating the average and change in the energy indices, energy savings and shares due to energy efficiency and structural shift at various intervals. The results, reported in Table A2 of the appendix, show variations in the indices across intervals at the country level. Overall, there are considerable variations across OPEC countries and time in respect of the decomposed energy indices.

The robustness of the highlighted results is checked by using the LMDI method to redo the decomposition analysis and the Spearman rank correlation to compare the resulting energy indices from both FII and LMDI. The high correlation coefficient (0.993) between energy efficiency indices from FII and LMDI methods and the high correlation coefficient (0.996) between the structural shift indices from FII and LMDI methods show that the results obtained using an alternative LMDI decomposition method are neither different nor superior to the highlighted results from the FII method.

3.3. Empirical results of the links between the energy indices and CO2 emissions

The results from the econometric analysis of the impact of the underlying factors of energy intensity on CO2 emissions controlling for other key factors are presented in this section. As discussed in subsection 3.2, the variables for the econometric analysis include CO2 emissions and income per capita, decomposed energy intensity indices and their squared terms to account for a possible nonlinear impact. We also control for cleaner energy substitution and trade openness. All of the variables are in a natural log, except for the two control variables, which are already in percentages. The summary statistics are in Table A1 of the Appendix.

Time series results

Using the maximum likelihood procedure in conjunction with the Kalman filter, the general STSM-ARDL (2, 2) model comprising equations (11–13) is estimated for each of the 14 OPEC countries for the period 1971–2014, saving 2015–2017 for stability and prediction test. The general-to-specific principle is used such that the parsimonious models, shown in Table 4, were found by testing down from the general model (with 2 years lags on all variables), eliminating statistically insignificant variables and determining the nature of the trend, but ensuring a range of diagnostics tests are passed. Almost all models reported in Table 4 fit the data well. Specifically, there are generally no problems with misspecification and instability (as indicated by the post-sample predictive failure test). The exception is Libya (where the model shows instability in the predictive failure test at 10 per cent level). The results of LR tests for all the preferred models clearly show that setting appropriate hyperparameters to zero for a deterministic trend is rejected so that the UCETs are stochastic, the exceptions being Algeria.
Table 4 Preferred STSMs of the link between energy indices and CO₂ emissions for OPEC country level, 1971–2017

| Dependent variable: co2 (carbon emissions in logs) |
|---------------------------------------------------|

| Regressors | ALG | ANG | CON | ECU | GAB | IRN | IRQ | KUW | LIB | NIG | QAT | SAR | UAE | VEN |
|------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| \( a_0(y) \) | 0.690*** | 2.565*** | 0.804*** | 1.059*** | 1.322*** | 0.893*** | 0.951*** | 0.613*** | 0.673*** | 4.582*** | 0.966** | 0.784*** | 1.173*** | 0.819*** |
| (0.095) | (0.249) | (0.145) | (0.117) | (0.209) | (0.026) | (0.154) | (0.075) | (0.078) | (0.727) | (0.394) | (0.079) | (0.085) | (0.103) |
| \( b_{0(eff)} \) | 1.074*** | 2.463*** | 0.835*** | 0.780*** | 1.041*** | 0.853*** | 1.583*** | 0.731*** | 0.425*** | 4.724*** | 1.000*** | 1.214*** | 0.901*** | 1.191*** |
| (0.104) | (0.225) | (0.117) | (0.075) | (0.129) | (0.059) | (0.274) | (0.082) | (0.109) | (0.702) | (0.210) | (0.090) | (0.061) | (0.176) |
| \( \gamma_0(ef^2) \) | −0.206** | −0.206** | −0.206** | −1.811*** | −1.450*** | 0.079* | −0.419** | −0.095** | −0.131** | −0.281* |
| (0.079) | (0.466) | (0.346) | (0.044) | (0.189) | (0.045) | (0.045) | (0.045) | (0.045) | (0.045) | (0.045) |
| \( \psi_0(act) \) | 0.972*** | 2.442*** | 0.979*** | 0.750*** | 1.421*** | 0.974*** | 1.557*** | 0.831*** | 0.610*** | 4.679*** | 0.734*** | 0.852*** | 0.912*** | 0.903*** |
| (0.167) | (0.235) | (0.140) | (0.070) | (0.217) | (0.061) | (0.204) | (0.121) | (0.088) | (0.685) | (0.407) | (0.135) | (0.061) | (0.101) |
| \( \alpha_0(TO) \) | 0.002* | 0.001* | 0.001* | 0.003* | −0.001** | −0.003** | −0.001** | −0.001** | −0.001** | −0.001** |
| (0.001) | (0.001) | (0.001) | (0.002) | (0.002) | (0.002) | (0.002) | (0.002) | (0.002) | (0.002) |
| \( \nu_0(ES) \) | −0.012*** | −0.028*** | −0.017*** | −0.013*** | −0.017*** | −0.065*** | −0.123*** | −0.014** | −2.535*** | −0.019*** |
| (0.003) | (0.002) | (0.002) | (0.007) | (0.007) | (0.007) | (0.007) | (0.007) | (0.007) | (0.007) |
| \( \lambda_1(CO2_{-1}) \) | 0.102* | −0.111** | −0.111** | 0.253*** | 0.091*** | −0.149** | −0.215* | −0.111* |
| (0.005) | (0.067)* | (0.067)* | (0.083) | (0.083) | (0.083) | (0.083) | (0.083) | (0.083) |
| \( \delta CO2_{/eff} \) | 0.782 | 2.463 | 0.835 | 0.949 | 0.956 | 0.937 | 1.132 | 0.731 | 0.611 | 4.724 | 1.000 | 0.870 | 0.901 | 1.493 |
| Nature of trend | LLTD | ST | ST | ST | LLT | ST | ST | LLTD | LLT | LLTD | ST | LLTD | LLTD | LLT |
| Interventions | L.1990 | 1.1984 | − | − | L.1976 | L.1989 | 1.1997 | − | − | − | L.1981 | L.1976 | 1.1994 |
| R-squares | 0.952 | 0.951 | 0.887 | 0.933 | 0.881 | 0.974 | 0.766 | 0.974 | 0.845 | 0.844 | 0.562 | 0.951 | 0.928 | 0.843 |
| LR test | 3.928 | 6.269 | 3.028 | 1646 | 2.317 | 2.327 | 5.189 | 1.429 | 7.340* | 1.018 | 0.058 | 1.623 | 5.822 | 2.966 |
| Cusum test | −1.066 | 1.828 | −1.308 | −0.503 | −0.858 | −0.680 | −0.621 | −1.569 | 0.527 | 0.197 | 0.700 | 0.446 | −0.655 |
| LR test | 0.970 | 32.489*** | 12.879*** | 12.538*** | 10.260*** | 19.628*** | 17.364*** | 18.928*** | 34.526*** | 22.547*** | 3.626* | 10.533** | 28.50*** | 34.719*** |
Table 4  Continued

Dependent variable: co2 (carbon emissions in logs)

| Regressors | ALG | ANG | CON | ECU | GAB | IRN | IRQ | KUW | LIB | NIG | QAT | SAR | UAE | VEN |
|------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Long-run elasticities | | | | | | | | | | | | | | |
| $\alpha^*(y)$ | 0.768 | 2.565 | 0.724 | 1.059 | 1.322 | 0.893 | 1.240 | 0.674 | 0.673 | 5.384 | 0.795 | 0.784 | 1.056 | 0.819 |
| $\beta^*(\text{eff})$ | 0.870 | 2.463 | 0.752 | 0.949 | 0.956 | 0.937 | 1.476 | 0.804 | 0.611 | 5.551 | 0.823 | 0.870 | 0.811 | 1.493 |
| $s^*(\text{act})$ | 1.082 | 2.442 | 0.881 | 0.750 | 1.421 | 0.974 | 2.030 | 0.914 | 0.610 | 5.498 | 0.604 | 0.832 | 0.821 | 0.903 |
| $\omega^*(\text{TO})$ | 0.147 | 0.082 | 0.233 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.074 | 0.000 | 0.000 | 0.000 | 0.000 |

***, ***, and * indicate 99%, 95%, and 90% significance levels, respectively; standard errors are in parenthesis; the marginal effect of energy efficiency $\partial \text{CO}_2/\partial \text{eff}$ is evaluated at the mean value.

Nature of trend: LLT is the local level trend (i.e., level $\neq 0$, $\sigma^2_\eta \neq 0$; slope $= 0$, $\sigma^2_\xi = 0$), LLTD is a local level trend with drift (i.e., level $\neq 0$, $\sigma^2_\eta \neq 0$; slope $\neq 0$, $\sigma^2_\xi = 0$), ST is a smooth trend model (i.e., level $\neq 0$, $\sigma^2_\eta = 0$; slope $\neq 0$, $\sigma^2_\xi \neq 0$), and LT is the local trend model (i.e., level $\neq 0$, $\sigma^2_\eta \neq 0$; slope $\neq 0$, $\sigma^2_\xi \neq 0$).

L. and I. represent level break and irregular intervention dummies, respectively, included where necessary (Harvey and Koopman, 1992).

Failure is the post-sample predictive failure test for 2015–2017 distributed approximately as $\chi^2_{(3)}$.

Cusum is the test of parameters consistency, approximately distributed as the t-distribution.

$LR$ is the likelihood ratio test of the restrictions that both hyperparameters $\sigma^2_\eta$ and $\sigma^2_\xi$ are equal to zero, distributed as $\chi^2_{(2)}$ or either $\sigma^2_\eta$ or $\sigma^2_\xi$, is equal to zero, distributed as $\chi^2_{(1)}$. $LR$ is expressed as $LR(p) = -2(LLR - LL_U) \sim \chi^2_p$ where $LL_U$, is the log-likelihood value for the unrestricted model; $LL_R$ is the log-likelihood value for the restricted model, and $r$ is the number of restrictions imposed on the hyperparameters.

Long-run elasticities are estimated based on the formula stated in footnote 17; the SR elasticities are the coefficients of the variables at levels and the marginal effect of energy (in)efficiency.
reported $R$-squares are satisfactorily high, implying that the final regressors in the preferred models explain a larger part of the changes in CO$_2$ emissions. In what follows, we discuss the estimated coefficients with some relevant policy and research implications.

The dynamic structures of the preferred model vary across the countries. Seven of the 14 countries displayed immediate adjustment to changes in the regressors (i.e. no dynamic term) despite starting with lags of 2 years, while the lagged dependent variable for the remaining seven countries is statistically significant. Of the seven countries with a dynamic model, four indicate a positive coefficient for the lagged CO$_2$ emissions. A positive sign may point to a lack of active policies (or incentives) in the past to abate CO$_2$ emissions, leading to a spillover effect that drives current CO$_2$ emissions to increase, while a negative sign may imply that the previous size of CO$_2$ emissions led to more stringent environmental policy, which makes subsequent CO$_2$ emissions to decline (Tajudeen et al., 2018).

Consistent with the results by Sari and Soytas (2009) and Arouri et al. (2012), income has a positive significant impact on CO$_2$ emissions, with some variations in the magnitude—ranging from 0.613 (for Kuwait) to 4.582 (for Nigeria); i.e. 0.61 per cent and 4.9 per cent increases in CO$_2$ emissions are attributed to a 1 per cent increase in income for Kuwait and Nigeria, respectively. Structural shift in economic activity also has a significant positive impact on CO$_2$ emissions. An increase in structural activities towards energy-intensive industries would increase CO$_2$ emissions and vice versa. The coefficients vary from 0.425 (for Libya) to 4.724 (for Nigeria). Similarly, the energy efficiency index has a positive impact on CO$_2$ emissions. Since an increased efficiency index implies deterioration in energy efficiency and vice versa, a positive relationship with CO$_2$ emissions implies that as the energy efficiency index increases CO$_2$ emissions increase. The coefficients vary from 0.610 (for Libya) to 4.679 (for Nigeria).

Also, the squared term of efficiency index shows a negative significant impact on CO$_2$ emission for Algeria, Ecuador, Gabon, Iraq and Saudi Arabia. Since these countries (except Ecuador) have increased efficiency index from the start, the nonlinear impact of energy efficiency on CO$_2$ emission forms an inverted U shape, indicating that their efficiency index increases CO$_2$ emissions to a certain threshold after which it starts to decline and CO$_2$ emissions decline. In contrast, there is a declining return to improving energy efficiency (in terms of a marginal reduction in CO$_2$ emission over time) for Ecuador. Likewise, the energy efficiency index and its squared term for IR Iran, Libya and Venezuela, which all have increased efficiency index from the start, show positive impacts on CO$_2$ emissions. Therefore, there are increasing impacts of IR Iran, Libya and Venezuela’s increasing efficiency indices (in terms of a greater increase in CO$_2$ emissions over time). For the remaining OPEC countries, efficiency index has a linear positive impact of CO$_2$ emissions. Thus, for Angola and Nigeria, which all have a
declining energy efficiency index (i.e. energy efficiency improvement) from the start, energy efficiency index continues to decrease CO₂ emissions at a constant rate and this trend does not seem to change as the squared term of energy efficiency index is insignificant.

Lastly, cleaner energy substitution and trade openness have significant impacts on CO₂ emissions. As expected, the share of cleaner energy generally has a negative effect on CO₂ emissions. The coefficients vary from −0.012 (for Angola) to −0.253 (for Saudi Arabia), suggesting that cleaner energy substitution is an important factor that has to be considered in a model of this nature. The impact of trade openness on CO₂ emissions confirms the mixed evidence in the literature on whether trade openness is good for the environment. E.g., the results for Algeria, Angola, Gabon and Saudi Arabia show that trade openness impacts CO₂ emissions positively. In contrast, the results for Iraq and Kuwait show that trade openness improves the environment while the remaining eight countries show no significant impact.

With some dynamics in the preferred models, we can separate the short-run from the long-run elasticities. There are variations in the LR income, efficiency, structural shift, cleaner energy substitution and trade openness elasticities of CO₂ emissions. Energy (in)efficiency index has the highest LR elasticities ranging from 0.611 (for Libya) to 5.551 (Nigeria). Next are the LR structural shift elasticities ranging from 0.604 (for Qatar) to 5.498 (for Nigeria) while the LR trade openness elasticities are the least ranging from 0.074 (Saudi Arabia) to 0.327 (for Kuwait), respectively.¹⁹ Consistent with the reported heterogeneous elasticities, the unobserved exogenous non-economic factors (ExNEF) represented in the estimated UCETs in Fig. 3 vary across the 14 OPEC countries considered as of 2018, reflecting country-specific effect.²⁰ This indicates that after controlling for structural shifts in economic activities, income, cleaner energy substitute and trade openness effects in the CO₂ emissions - energy (in)efficiency model, there are still other key exogenous influences driving CO₂ emissions. Specifically, the UCETs are associated with behavioural effects such as lifestyles and tastes, increasing awareness and attitudes towards the environment (Chitnis and Hunt, 2012; Tajudeen, 2015; Adetutu et al., 2016).

The general trends of the estimated UCETs for Algeria, Angola, IR Iran, Kuwait, Libya, UAE, and Venezuela are upward sloping over the estimation period, suggesting increasing ‘carbon-emitting’ behaviour and lifestyle. In contrast, Congo, Ecuador, Gabon, Iraq, Nigeria, Qatar and Saudi Arabia have downward sloping trends over time, showing exogenous ‘carbon mitigating’ behaviour and lifestyle. Thus, there are improving behaviours and lifestyle that support environmental sustainability in the latter seven countries. These results highlight the reason not to ignore exogenous non-economic factors (ExNEF), e.g. values, tastes and lifestyle in the environmental models for energy-intensive countries such as OPEC countries.
Lastly, to shed more light on the relative influence of the energy intensity indices and ExNEF on the environment, we quantify the contributions of the different drivers of the annual change in CO₂ emissions for OPEC using the model given by equation (16). The estimated contributions of the different components, i.e. income, (in)efficiency, structural shift, cleaner energy substitute, trade openness and ExNEF to the annual change in fitted CO₂ emissions over the period 1971–2014, ²¹ are shown in Fig. 4 and summarised in Table 5. The figure shows that for many of the countries considered, energy inefficiency and ExNEF contribute considerably to the annual change in CO₂ emissions compared to other variable factors. Overall, for most OPEC countries, deteriorating energy efficiency has the largest positive contribution in driving up the average per annum change in CO₂ emissions, followed by income, the structural shift towards energy-intensive sectors and ExNEF.

In contrast, improving energy efficiency (for Ecuador and Nigeria), as well as cleaner energy substitute and trade openness, to an extent, is driving down annual change in CO₂ emissions. The average annual change in fitted CO₂ emissions is positive for all OPEC countries. The robustness of the results is checked by comparing the average annual change in fitted CO₂ emissions (ΔCO2) to the change in actual CO₂ emissions (ΔCO2). The last two columns of Table 5 show that the two estimates are similar in value and identical in sign. Also, the fitted change is in line with the actual change in a long term

**Table 5**

| Country | ΔbCO₂ | ΔCO₂ |
|---------|-------|------|
| Algeria | –22.3 | –21.8 |
| Angola  | –5.6  | –5.4  |
| Congo   | –8.3  | –8.3  |
| Ecuador | –11.5 | –11.3 |
| Gabon   | –7.4  | –7.3  |
| IR Iran | –4.3  | –4.1  |
| Iraq    | –7.4  | –7.3  |
| Kuwait  | –7.3  | –7.2  |
| Libya   | –8.1  | –7.7  |
| Libya   | –8.2  | –7.3  |
| Qatar   | –5.6  | –5.4  |
| Saudi Arabia | –35.2 | –35.0 |
| UAE     | –8.1  | –6.3  |
| Venezuela | –6.3  | –6.3  |

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Figure 4 Contributions to the annual change in CO₂ emissions ΔCO₂ (in logs), OPEC country-level.
Figure 4 Continued.

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indicating that the results of the relative contributions of the drivers are reliable for policy formulation.

**Panel data results**

The panel data model is estimated to complement the time series results of the links between the decomposed energy indices and CO₂ emissions for OPEC as a group. Since we found Angola, Ecuador and Nigeria to have become more energy efficient from the decomposition analysis, to ensure that the impact of the energy intensity indices on CO₂ emissions is well estimated, the panel data analysis is estimated with (and without) the three countries. We report the static panel regression specified in equation (14) and estimated by FE in columns I (all OPEC) and II (OPEC but excluding the three energy-efficient countries) of Table 6. The dynamic panel regression specified in equation (15) and estimated by LSDVC is reported in columns III (all OPEC) and IV (OPEC excluding the three energy-efficient countries) of Table 6.

We start by discussing the diagnostic tests addressing the econometric issues that may arise in the panel model. The panel data model specified in equation (14) may be prone to some econometric issues including observed and unobserved heterogeneity, endogeneity and cross-section dependence. The unobserved heterogeneity can be dealt with an FE or RE estimation method. The Hausman test for correlated fixed effects \( \chi^2 = 14.80 \) (pval = 0.02) for panel I and \( \chi^2 = 23.46 \) (pval = 0.00) for panel II (excluding the energy-efficient countries from the group) rejects the null of exogeneity in
favour of the FE over the RE method. Therefore, we used FE to address unobserved heterogeneity while the control variables, trade openness and cleaner energy substitution rate are used as controls for observed heterogeneity.

Endogeneity problems may arise from the variables, in particular, with regard to the energy (in)efficiency, structural shift and trade openness variables. E.g., the advent of an unobserved country and time-specific factors such as natural gas fracking would increase energy supply or electricity generation, hence leading to energy inefficiency. It might also change the cost of energy inputs into production, thus leading to a structural shift to more energy-intensive activities. Also, the recipients’ policy on tariff and profit tax would influence trade intensity. Since the highlighted factors (i.e. natural gas fracking, tariffs and profit tax) are not included in the model, they are contained in the error term, thus may correlate with energy (in)efficiency, structural shift, and trade openness. We used the Durbin–Wu–Hausman technique to test for endogeneity of the explanatory variables using their lags as instruments.22

The endogeneity test failed to reject the null hypothesis of exogeneity for income, energy (in)efficiency, structural shift, trade openness and cleaner energy substitution

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**Table 5** Contribution to the average annual change in CO₂ emissions (in logs)

| Country | Ave (1971–2017) percentage contributions from: | Fitted ΔCO₂ | Actual ΔCO₂ |
|---------|-----------------------------------------------|--------------|-------------|
|         | y   | eff | act | TO | ES | ExNEF | ΔCO₂ | ΔCO₂ |
| Algeria | 1.183 | 2.008 | 0.295 | −0.034 | 0.000 | 0.434 | 3.887 | 3.964 |
| Angola  | −0.536 | 0.361 | −0.993 | 0.035 | 0.929 | 2.539 | 2.335 | 2.788 |
| Congo   | 0.962 | 0.934 | −1.537 | 0.000 | 0.117 | −0.017 | 0.459 | 0.637 |
| Ecuador | 1.835 | −0.228 | 0.395 | 0.000 | 0.327 | −0.125 | 2.204 | 3.392 |
| Gabon   | 0.459 | 0.685 | 1.456 | 0.062 | −0.533 | 0.358 | 2.487 | 1.791 |
| IR Iran | −0.208 | 1.933 | 1.952 | 0.000 | 0.001 | 0.202 | 3.880 | 3.899 |
| Iraq    | 1.233 | 1.949 | 0.572 | 0.038 | −0.001 | −1.087 | 2.706 | 3.235 |
| Kuwait  | −1.396 | 0.345 | −1.756 | −0.107 | 0.000 | −0.021 | 0.578 | 0.487 |
| Libya   | −2.278 | 2.903 | 0.595 | 0.000 | 0.024 | 0.725 | 1.968 | 3.537 |
| Nigeria | 5.677 | −3.140 | 0.967 | 0.000 | 0.609 | −0.661 | 3.452 | 3.773 |
| Qatar   | −0.571 | 2.670 | 0.170 | 0.000 | 0.000 | −2.128 | 0.141 | 0.824 |
| Saudi   | −0.348 | 3.089 | 1.297 | 0.019 | 0.000 | 0.190 | 4.248 | 4.811 |
| UAE     | −2.862 | 0.251 | 2.938 | 0.000 | 0.000 | 1.329 | 1.656 | 1.998 |
| Venezuela | 0.154 | 1.450 | −0.542 | 0.000 | −0.019 | 0.159 | 1.202 | 0.574 |

The contributions are based on equation (16); we derive fitted changes in CO₂ emissions (ΔCO₂) by adding the estimated contributions from the variables; actual change in CO₂ emissions (ΔCO₂) is from the original data.
Table 6 Estimated panel data of the drivers of OPEC CO2 emissions, 1971–2017

Dependent variable: CO2 (carbon emissions in logs)

| Estimation method: | FE | FE | LSDVC | LSDVC |
|-------------------|----|----|-------|-------|
| Regressors:       | I  | II | III   | IV    |
| $\phi_0$ (Constant) | $-5.371^{***}$ | $-6.014^{***}$ | $-0.081^{**}$ | $-6.014^{***}$ | $-0.081^{**}$ |
|                   | (0.196) | (0.357) | (0.038) | (0.041) | (0.038) |
| $\alpha_0(y)$     | $0.698^{***}$ | $0.760^{***}$ | $0.438^{***}$ | $0.477^{***}$ | $0.438^{***}$ | $0.477^{***}$ |
|                   | (0.020) | (0.034) | (0.028) | (0.030) | (0.028) | (0.030) |
| $\beta_0(\text{eff})$ | $0.881^{***}$ | $0.870^{***}$ | $0.533^{***}$ | $0.527^{***}$ | $0.533^{***}$ | $0.527^{***}$ |
|                   | (0.032) | (0.028) | (0.013) | (0.014) | (0.013) | (0.014) |
| $\gamma_0(\text{eff})^2$ | $-0.081^{**}$ | $-0.056^{*}$ | $-0.045^{***}$ | $-0.031^{**}$ | $-0.045^{***}$ | $-0.031^{**}$ |
|                   | (0.032) | (0.028) | (0.013) | (0.014) | (0.013) | (0.014) |
| $\varphi_0(\text{act})$ | $0.798^{***}$ | $0.889^{***}$ | $0.465^{***}$ | $0.521^{***}$ | $0.465^{***}$ | $0.521^{***}$ |
|                   | (0.019) | (0.039) | (0.027) | (0.035) | (0.027) | (0.035) |
| $\omega_0(\text{TO})$ | $-0.001^{***}$ | $-0.001^{***}$ | $-0.001^{***}$ | $-0.001^{***}$ | $-0.001^{***}$ | $-0.001^{***}$ |
|                   | (0.000) | (0.000) | (0.000) | (0.000) | (0.000) | (0.000) |
| $\psi_0(\text{ES})$ | $-0.023^{***}$ | $-0.020^{***}$ | $-0.013^{***}$ | $-0.012^{***}$ | $-0.013^{***}$ | $-0.012^{***}$ |
|                   | (0.002) | (0.004) | (0.001) | (0.001) | (0.001) | (0.001) |
| $\lambda_1(\text{CO2}_t)$ | $-0.081^{***}$ | $-0.081^{***}$ | $-0.081^{***}$ | $-0.081^{***}$ | $-0.081^{***}$ | $-0.081^{***}$ |
|                   | (0.024) | (0.027) | (0.027) | (0.029) | (0.027) | (0.029) |
| Marginal effect: $\partial \text{CO2}/\partial \text{eff}$ | $0.808^{***}$ | $0.810^{***}$ | $0.491^{***}$ | $0.494^{***}$ | $0.491^{***}$ | $0.494^{***}$ |
|                   | (0.027) | (0.027) | (0.027) | (0.029) | (0.027) | (0.029) |
| Time dummies included | Yes | Yes | Yes | Yes |
| Observations | 658 | 517 | 644 | 506 |
| No. of countries | 14 | 11 | 14 | 11 |
| Diagnostics: | | | | | |
| $R^2$ | 0.897 | 0.901 | $-0.081^{***}$ | $-0.081^{***}$ |
| $F$ – test | 4545.51$^{***}$ | 4298.73$^{***}$ | $-0.081^{***}$ | $-0.081^{***}$ |
| Hausman ($\chi^2$) | 14.80$^{**}$ | 23.46$^{***}$ | $-0.081^{***}$ | $-0.081^{***}$ |
| Restriction test I: $\theta_t = 0$ | 248.25$^{***}$ | 384.50$^{***}$ | 104.20$^{***}$ | 77.01$^{***}$ |
| Elasticities | SR (III) | SR (IV) | LR (III) | LR (IV) |
| $\alpha^*(y)$ | $0.438^{***}$ | $0.477^{***}$ | $0.789^{***}$ | $0.843^{***}$ |
| $\beta^*(\text{eff})$ | $0.491^{***}$ | $0.494^{***}$ | $0.885^{***}$ | $0.873^{***}$ |
| $\varphi^*(\text{act})$ | $0.465^{***}$ | $0.521^{***}$ | $0.838^{***}$ | $0.922^{***}$ |
| $\omega^*(\text{TO})$ | $-0.047^{***}$ | $-0.063^{***}$ | $-0.085^{***}$ | $-0.111^{***}$ |
| $\psi^*(\text{ES})$ | $-0.290^{***}$ | $-0.149^{***}$ | $-0.522^{***}$ | $-0.264^{***}$ |
| Relative contributions | SR (III) | SR (IV) | LR (III) | LR (IV) |
| $y$ | 0.139% | 0.117% | 0.250% | 0.206% |
| $\text{eff}$ | 0.541% | 0.904% | 0.974% | 1.597% |
variables with $\chi^2$ equal to 0.21 ($pval = 0.65$), 0.43 ($pval = 0.51$), 0.98 ($pval = 0.32$), 1.84 ($pval = 0.18$) and 0.98 ($pval = 0.32$), respectively, for panel I. We found similar endogeneity results when panel II is used, and the overall results using the IVs remain unchanged from the FE estimations.

We also conduct a test for cross-sectional correlation using the Frees (1995, 2004) test, which follows a Q-distribution and suitable for a balanced panel as in this case. The Frees test values 0.79 ($pval = 0.00$) and 0.64 ($pval = 0.00$) for the panel I and panel II, respectively, reject the null hypothesis of cross-sectional independence. Therefore, we report the Driscoll and Kraay (1998) standard error for the FE results, which is robust to very general forms of cross-sectional and temporal dependence.

Lastly, the estimates of the standard F-test reject the null hypothesis that the time dummies are jointly equal to zero for panels I and II, implying that time dummies are a
good proxy for UCETs in the panel model. Table 6 shows that the estimated coefficients of the variables are significant and have the expected signs for the estimated models.

For panel I, energy (in)efficiency has a nonlinear effect on CO₂ emissions. The degrees of impact of a 1 per cent increase in energy (in)efficiency and structural shift indices on CO₂ emissions are 0.808 per cent and 0.798 per cent increases, respectively. Trade openness has the least significant effect and shows that trade is good for the environment, which slightly deviates from the mixed evidence from the time series model.

For panel II, the static model shows major changes in the coefficients. In particular, the marginal effect of energy (in)efficiency increases from 0.808 to 0.810. In other words, the inclusion of the energy-efficient countries in the panel data has a significant impact in driving down the net effect of energy inefficiency on CO₂ emissions. For the dynamic panel models (i.e. panels III and IV), all of the parameter estimates including the lagged dependent variable are significant with the expected signs. The lagged CO₂ emissions variable shows a positive impact on the current level of CO₂ emissions. The elasticities from the estimated LSDVC show variations between the SR(III) and LR(III) elasticities. The LR elasticities are significantly higher than the SR elasticities. Specifically, the LR income, (in)efficiency, structural shift, trade openness and cleaner energy substitution elasticities are about twice the corresponding SR elasticities, indicating that the variable factors are more associated to CO₂ emissions in LR than they do in SR.

There are also noticeable differences in the elasticities between panel III and IV. More importantly, the LR elasticities are comparable with the counterparts from the time series model. E.g., the LR income (0.79), energy (in)efficiency (0.89), structural shift (0.84), cleaner energy substitution (−0.52) and trade openness (−0.09) elasticities for panel III fall in the range of (0.67) – (5.14), (0.81) – (5.55), (0.60) – (5.50), (−0.02) – (−1.62), and (−0.33) – (0.07) for the counterparts’ elasticities from the country-level time series models reported in Table 4.

The panel data version of the UCET given by the estimated coefficients of the time dummies is represented in Fig. 5. If there has been significant progress in the ExNEF, i.e. positive lifestyles, tastes and behaviours towards the environment, which drive the UCET, we expect the UCET estimated as \( \theta (1/1 - \lambda) \) to be reflected in declining values (Harvey, 1989). In Fig. 5, the long-run UCET for OPEC as a group reflects variation from year to year as with the estimated UCETs for OPEC country-level analysis. The big fall in 1990–1992 corresponds to the period of the Gulf War I period and then followed by a rebound in 1993. Overall, the implicit trend of the UCET slopes upward over the estimation period—indicating a ‘carbon-emitting’ behaviour and other non-economic effects. This is expected given that the estimated UCETs for seven of the 14 countries show upward slopping trends in the country-level analysis. Also, excluding the three
countries that are found to have become more energy efficient makes the UCET trend for OPEC as a group (model IV) to shift further upward.

Lastly, using the panel data version of equation (16), we quantify the contribution of the drivers to the annual change in CO2 emissions. This is represented in Fig. 6 and summarised at the bottom of Table 6. The results further highlight the impact of changes in energy inefficiency and ExNEF (captured by the UCET) on the environment. It is clear from Fig. 6 that before 1990–92, the period of the Gulf War I, contributions from failing energy efficiency and structural shift are the main drivers of the positive annual change in CO2 emissions for OPEC as in Table 6 (panel III (LR(III))) while income makes a negative contribution. This trend was partly reversed after 1990–92, income and structural shift became key positive contributors to the annual change in CO2 emissions, and improvement in energy efficiency is seen now driving down annual growth in CO2 emissions. ExNEF makes both positive and negative contributions. Notwithstanding our findings that trade openness and substitution with cleaner energy are good for the environment, they generally make positive contributions to the annual change in OPEC’s CO2 emissions over the period. This is because, during the period considered, OPEC trade openness and cleaner energy usage declined. Specifically, OPEC’s trade openness and renewable energy share which stood at 82.05 per cent and 37.93 per cent in 1971

Figure 5 Estimated UCETs in logs (μ) for OPEC’s panel LSDVC, 1971–2017.
declined to 69.04 per cent and 14.19 per cent, respectively, in 2017, which led to 0.22 per cent and 0.27 per cent respective increase in CO₂ emissions as in Table 6 (panel III (LR(III))).

In all, deteriorating energy efficiency has the largest positive contribution, on average 0.97 per cent per annum, so that in addition to the net positive contributions from structural shift (0.62 per cent per annum), cleaner energy share (0.27 per cent per annum), income (0.25 per cent per annum), ExNEF (0.20 per cent per annum) and trade openness (0.02 per cent per annum), the average per annum change in CO₂ emissions for OPEC as a group increases significantly. These results are broadly consistent with the OPEC country-level results in Table 6.

4. Concluding remarks with policy implications

This paper examines the contributions from changes in energy efficiency and structural shifts in economic activity to the overall changes in energy intensity as well as their environmental implications for 14 OPEC countries over the period 1971–2017. To achieve this, we use an index decomposition analysis (IDA) based on the Fisher Ideal
Index to decompose the OPEC energy intensity index into an energy efficiency index and a structural shift index. Next, we use structural time series and bias-corrected least square variable model to analyse the link between the IDA-based energy (in)efficiency and structural shift indices and CO₂ emissions while controlling for economic and non-economic factors such as taste, lifestyle and attitude.

Our findings from the index decomposition analysis of energy intensity show that for OPEC as a group, an increase in energy intensity was associated with both inefficient energy use and structural shift towards energy-intensive activities. Specifically, about 62.11 per cent of the increase in energy intensity index since 1971 is attributed to the former while the remaining 37.89 per cent is attributed to the latter. The country-level analysis results also suggest significant contributions from both energy inefficiency and structural shift in economy composition to energy intensity. For instance, increases in energy intensity index attributed to deteriorating energy efficiency range from 3.0 per cent (for UAE) to 1000 per cent (for Congo). In contrast, the results for Angola, Ecuador and Nigeria show improving energy efficiency.

The results from the econometric analysis highlight some important effects. For the panel of OPEC countries, deteriorating energy efficiency and structural shift towards energy-intensive activities are found to have significant positive effects on CO₂ emissions. Trade openness and cleaner energy substitution are found to be good for the environment. These impacts are generally larger in the long run (than the short run). Moreover, the time series results for the OPEC country level are largely consistent with the panel data results, the exception being trade openness which is found to have a mixed impact on the environment.

More importantly, the underlying carbon emission trend (UCET) which arguably reflects the impact of the exogenous non-economic factors shows an upward sloping trend for OPEC a group indicating carbon-emitting lifestyles, tastes, attitudes and other non-economic effects on the environment. The upward trend at the group level suggests a dominant effect of the various upward sloping UECTs found for Algeria, Angola, IR Iran, Kuwait, Libya UAE and Venezuela from the country-level time series results over the downward sloping UECTs (indicating carbon mitigating lifestyles, tastes attitudes and other non-economic effects on the environment) found for Congo, Ecuador Gabon, Iraq, Nigeria, Qatar and Saudi Arabia.

Lastly, the quantification of both the economic and non-economic drivers of OPEC’s CO₂ emissions further highlights the influence of these variables. Deteriorating energy efficiency is found to explain the larger part of the annual growth in CO₂ emissions, on average 0.97 per cent per annum so that in addition to the net positive contributions from structural shift (0.62 per cent per annum), income (0.25 per cent per annum) and the non-economic factors (0.20 per cent per annum) the average annual change in OPEC’s CO₂ emissions increases significantly.
In conclusion, the insight generated by this paper is that, over the last 47 years, the underlying trends of the energy intensity, behavioural and other non-economic influences in some of the OPEC countries do not align with environmental sustainability. This, perhaps, reflects the ‘effect’ of the generally low energy prices via a wide variety of energy subsidy policy adopted in the oil-exporting countries. Consequently, the message for policymakers is that policies aimed at conserving energy and restraining the concentration of energy-intensive activities in the oil-exporting countries are crucial. Besides, other policies that attempt to influence behavioural change—lifestyles, tastes and attitudes, and other non-economic factors—also need to be considered.

Notes

1. Computed by the authors based on data sourced from IEA accessed via http://stats.ukdataservice.ac.uk
2. Following Metcalf (2008), structural change refers to a shift in the sectoral composition of the economy; e.g., a shift away from a light industry to heavy industry that are usually energy intensive and vice versa.
3. Energy price subsidies have been a common energy policy for most oil-exporting countries that make up OPEC. Specifically, Friedrichs and Inderwildi (2013) reported that the combined fuel price for gasoline and diesel in 2010 in OPEC countries was less than US $1.35 per litre and was found to be one of the cheapest fuel prices in the world.
4. The Paris Agreement (PA), starting in the year 2020, aims to strengthen the global response to the climate change risk by keeping a global temperature rise to well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5°C. PA went into effect on 4 November 2016 after the threshold for entry into force was achieved on 5 October 2016. As of March 2020, 197 members have signed the treaty, 189 of which have ratified it (UNFCCC, available at www.unfccc.int).
5. The efficiency index (also known as the technical change) therefore attributes the actual changes in the level of energy intensity to efficiency change holding structural changes constant, and the activity index attributes changes in energy intensity to structural changes in economic activities holding efficiency across sectors constant (Moshiri and Duah, 2016; Inglesi-Lotz and Pouris, 2012).
6. We proxy cleaner energy substitute by alternative and nuclear energy (% of energy use) and trade openness by trade (% of GDP)
7. The total effect of $EF$ and $ACT$ are derived as $\partial CO_2_i/\partial EF_i = \beta_0 + 2\gamma_0 EF_i$ and $\partial CO_2_i/\partial ACT_i = \phi_0 + 2\Phi_0 ACT_i$, respectively.
8. Note that in Eq. (11), with the incorporation of energy efficiency index, we have separated the effect of technical progress and/or energy efficiency from ExNEF. Hence, the estimated UCET should only pick up the other exogenous effects of such factors as preferences, lifestyle, values, attitudes and environmental awareness (Broadstock and Hunt, 2012; Chitnis and Hunt, 2012).
9. The long-run income, efficiency, structural shift, cleaner energy substitute and trade openness elasticities are given as
\[ \alpha^* = \frac{\alpha(L)}{\lambda(L)}, \beta^* = \frac{\beta(L) + 2\gamma(L) - \epsilon_t}{\lambda(L)}, \gamma^* = \frac{\phi(L) + 2\Phi(L) - \lambda(L)}{\lambda(L)} \]
10. An important assumption for the three combined models is that the error terms \( \epsilon_t, \eta_t, \text{and} \xi_t \) are independent and uncorrelated.
11. Given that the deterministic restriction is on the hyperparameters, the LR test is suitable to test the validity of this restriction.
12. I.e., \( \mu_t \) will collapse to \( \mu_t = \phi_0 + b_0t \) where \( \phi_0 \) is a constant and \( t \) is a deterministic linear trend with the coefficient \( b_0 \)
13. E.g., for the time series model, it is derived as
\[ \Delta co2_t = \Delta \mu_t + \alpha_0 \Delta y_t + \beta_0 ^* \Delta ef_t + \gamma_0 ^* \Delta act_t + \psi_0 \Delta ES_t + \omega_0 \Delta TO_t \]
where \( \alpha_0, \beta_0 ^*, \gamma_0 ^* \), and \( \omega_0 \) are the estimated impact of income, energy (in)efficiency, structural shift, cleaner energy substitute and trade openness on CO2 emissions, respectively, and \( \mu_t \) is the estimated UCET. Thus, \( \alpha_0 \Delta y_t, \beta_0 ^* \Delta ef_t, \gamma_0 ^* \Delta act_t, \omega_0 \Delta TO_t \), and \( \Delta \mu_t \) represent the estimated contributions of the corresponding variables to the annual change in CO2 emissions.
14. We derive \( \Delta co2_a \) and \( \Delta y_t ^a \) by aggregating the variables across countries, divide it by the combined population and then take the log; \( eff_t ^a \) and \( act_t ^a \) are the logs of the resulting efficiency and activity indices from the decomposed energy intensity for OPEC as a group; \( ESt _t ^a \) and \( TO _t ^a \) are the cleaner energy share (as a % of energy use) and trade openness (as a % of GDP) for OPEC as a group.
15. It is noteworthy to mention that, as at 2018, OPEC comprised of 15 countries including Algeria (ALG), Angola (ANG), Congo (CON), Ecuador (ECU), Equatorial Guinea (EQU), Gabon (GAB), IR Iran (IRN), Iraq (IRQ), Libya (LIB), Kuwait (KUW), Nigeria (NIG), Qatar (QAT), Saudi Arabia (SAD), United Arab Emirates (UAE) and Venezuela (VEN). However, due to lack of data, this study focuses on 14 OPEC countries excluding Equatorial Guinea.
16. Note that a decline in energy intensity index from its base value is regarded as an improvement and by construction; a decline in efficiency index is regarded as improved energy efficiency while an increase is regarded as deteriorated efficiency (i.e. energy inefficiency). Similarly, a declining activity index represents structural shifts in favour of less energy-intensive sectors and vice versa. Thus, improvements are used interchangeably for declining indices while deteriorations are used for increasing indices.
17. E.g., the average energy self-sufficiency (ESS) (calculated as the total energy production (TEP)/total primary energy supply (TPES)) for the 14 countries in 2017 is 2.71 but Angola, Ecuador and Nigeria have ESS of 6.26(14th), 2.07(12th) and 1.59(14th), respectively. Also, the average TPES per capita (TPES/population) for the 14 countries in 2017 is 2.10tones of oil equivalent (toe) but Angola, Ecuador and Nigeria have TPES per capita of 0.49toe (14th), 0.87toe (11th) and 0.82toe (12th), respectively (IEA, 2015).
18. E.g., Angola has the highest gasoline price (0.97US$/litre) and diesel price (in 0.82US$/litre) in 2016 (World Bank, 2020).
19. The LR elasticities are derived using the formula in footnote 9; the SR elasticities are the coefficients of the variables at levels.
20. The UCETs in Fig 3 indicates various patterns for all of the countries, and most of them is found not to be fixed, i.e., $\sigma^2_\eta$ and $\sigma^2_\xi$ in Eqs (12) - (13) are not jointly equal to zero, the exception is Algeria. They stochastically change directions over the estimation period and not at a fixed rate, as a deterministic model would suggest.

21. Given that the data for the period 2015-2017 have been used for predictive failure tests, as with the final estimated models, the quantification of the contributions of the drivers is based on 1971-2014.

22. We use the lags of the potential endogenous variables as instruments since the lagged variable is less likely to be influenced by current shocks. Moreover, it is not easy to come up with other valid instruments since many available macroeconomic variables are all interrelated and may not be devoid of endogenous issues.

SUPPORTING INFORMATION
Additional supporting information may be found online in the Supporting Information section at the end of the article.

Data and estimation codes and sheets

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## Table A1 Summary statistics of the variables for OPEC countries

| Country | Stat. | Economic activity (in billion 2015 US$) | Energy demand in million tonnes of oil equivalent (Mtoe) | Data for analysing the drivers of CO₂ emissions |
|---------|-------|----------------------------------------|-------------------------------------------------------|-----------------------------------------------|
|         |       | Data for energy intensity index decomposition analysis |
|         |       | | Y | E₁ | E₂ | E₃ | E₄ | E₅ | E₆ | E₇ | E | co₂ | y | TO | ES |
| Algeria | Mean  | 30.08 | 4.46 | 7.12 | 6.91 | 7.80 | 28.92 | 36.59 | 93.94 | 6.23 | 3.07 | 0.80 | 6.13 | 0.11 | 0.52 | 4.24 | 21.09 |
| SD      |       | 7.56  | 1.57 | 5.11 | 4.35 | 5.19 | 16.21 | 14.94 | 38.77 | 2.32 | 1.87 | 0.71 | 4.26 | 0.12 | 0.80 | 2.90 | 11.90 |
| Angola  | Mean  | 12.06 | 3.49 | 4.84 | 2.21 | 4.79 | 27.29 | 26.19 | 50.62 | 0.21 | 0.61 | 0.05 | 0.85 | 0.01 | 0.30 | 3.65 | 5.67  |
| SD      |       | 8.18  | 1.74 | 4.44 | 1.52 | 2.28 | 10.28 | 14.97 | 30.44 | 0.15 | 0.32 | 0.06 | 0.81 | 0.01 | 0.33 | 1.02 | 2.53  |
| Ecuador | Mean  | 2.18  | 0.43 | 0.55 | 0.54 | 0.44 | 1.69 | 2.97  | 6.17  | 0.04 | 0.03 | 0.00 | 0.24 | 0.00 | 0.02 | 0.51 | 0.85  |
| SD      |       | 1.17  | 0.20 | 0.60 | 0.27 | 0.18 | 0.80 | 1.43  | 2.91  | 0.04 | 0.02 | 0.00 | 0.16 | 0.00 | 0.06 | 0.29 | 0.53  |
| Gabon   | Mean  | 3.03  | 8.37 | 5.38 | 2.87 | 4.75 | 24.31 | 33.90 | 53.90 | 0.89 | 1.31 | 0.07 | 2.74 | 0.10 | 0.63 | 1.34 | 7.08  |
| SD      |       | 1.69  | 3.56 | 2.39 | 1.83 | 2.40 | 10.16 | 14.66 | 23.41 | 0.56 | 0.59 | 0.09 | 1.43 | 0.07 | 0.66 | 0.18 | 3.25  |
| Iran    | Mean  | 6.42  | 0.41 | 0.33 | 0.38 | 0.39 | 2.58 | 3.04  | 9.46  | 0.05 | 0.10 | 0.00 | 0.13 | 0.01 | 0.03 | 0.78 | 2.02  |
| SD      |       | 1.68  | 0.25 | 0.23 | 0.19 | 0.12 | 1.09 | 1.06  | 2.51  | 0.03 | 0.10 | 0.00 | 0.07 | 0.01 | 0.02 | 0.27 | 1.43  |
| Iraq    | Mean  | 69.81 | 22.24 | 19.85 | 18.93 | 22.58 | 114.17 | 113.27 | 261.88 | 10.91 | 25.54 | 0.00 | 21.53 | 4.07 | 6.87 | 24.15 | 93.06 |
| SD      |       | 24.99 | 16.94 | 6.62 | 13.87 | 10.56 | 38.64 | 57.82 | 91.07 | 7.84 | 18.92 | 0.00 | 14.57 | 1.94 | 3.82 | 17.40 | 63.21 |
| Kuwait  | Mean  | 28.05 | 4.88 | 3.21 | 10.43 | 6.78 | 26.57 | 31.28 | 79.06 | 2.51 | 3.19 | 0.00 | 6.55 | 0.00 | 0.87 | 2.97 | 16.08 |
| SD      |       | 15.87 | 1.72 | 4.50 | 2.24 | 23.54 | 27.79 | 43.40 | 7.84 | 18.92 | 0.00 | 14.57 | 1.94 | 3.82 | 17.40 | 63.21 |
| Libya   | Mean  | 31.29 | 6.06 | 2.45 | 2.98 | 0.24 | 28.52 | 27.61 | 65.09 | 4.35 | 3.38 | 0.00 | 2.48 | 0.00 | 1.23 | 1.31 | 12.75 |
| SD      |       | 14.43 | 1.89 | 0.79 | 3.08 | 0.19 | 16.69 | 12.48 | 28.35 | 2.63 | 2.45 | 0.00 | 1.30 | 0.00 | 0.95 | 0.78 | 6.80  |
| Nigeria | Mean  | 82.14 | 3.40 | 1.02 | 1.67 | 0.81 | 16.19 | 14.60 | 85.35 | 2.07 | 2.34 | 0.00 | 3.05 | 0.10 | 0.22 | 0.93 | 8.71  |
| SD      |       | 32.83 | 1.94 | 0.60 | 1.10 | 0.36 | 7.01 | 11.40 | 31.01 | 1.09 | 1.25 | 0.00 | 1.74 | 0.05 | 0.32 | 0.44 | 3.66  |
| Qatar   | Mean  | 35.71 | 27.00 | 6.20 | 15.54 | 41.26 | 82.74 | 177.67 | 219.23 | 2.98 | 4.03 | 0.00 | 6.81 | 0.03 | 1.63 | 59.76 | 75.24 |
| SD      |       | 8.84  | 8.45 | 4.47 | 20.72 | 30.59 | 62.40 | 106.12 | 123.53 | 1.75 | 3.07 | 0.00 | 4.16 | 0.04 | 1.50 | 21.30 | 31.08 |
| Saudi   | Mean  | 21.29 | 4.97 | 3.34 | 1.96 | 0.13 | 17.37 | 11.40 | 49.44 | 3.89 | 4.51 | 0.00 | 1.24 | 0.00 | 0.32 | 0.38 | 10.34 |
|         |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |
Table A1  Continued

Data for energy intensity index decomposition analysis

| Country       | Stat. | Y_1 | Y_2 | Y_3 | Y_4 | Y_5 | Y_6 | Y_7 | Y  | E_1 | E_2 | E_3 | E_4 | E_5 | E_6 | E_7 | E  | CO2 | y  | TO  | ES  |
|---------------|-------|-----|-----|-----|-----|-----|-----|-----|----|-----|-----|-----|-----|-----|-----|----|----|----|----|----|
| UAE Mean      | SD    | 20.39 | 4.12 | 5.75 | 2.94 | 0.05 | 19.69 | 10.46 | 50.95 | 4.62 | 3.41 | 0.00 | 1.31 | 0.00 | 0.29 | 0.43 | 9.94 | 6.22 | 15.78 | 11.76 | 0.00 |
|              |       | 31.65 | 23.22 | 9.68 | 12.29 | 4.94 | 74.87 | 70.02 | 135.93 | 4.52 | 23.18 | 0.00 | 12.96 | 0.14 | 2.39 | 4.47 | 47.10 | 4.03 | 6.93 | 10.25 | 0.01 |
| Venezuela     | Mean  | 59.72 | 13.31 | 15.66 | 12.50 | 1.83 | 65.69 | 77.53 | 167.81 | 1.05 | 14.06 | 0.00 | 5.10 | 0.02 | 1.53 | 1.28 | 23.03 | 21.90 | 64.76 | 100.4 | 0.05 |
|              | SD    | 18.05 | 10.75 | 10.53 | 11.29 | 1.17 | 48.75 | 53.68 | 100.82 | 0.85 | 10.36 | 0.00 | 3.67 | 0.02 | 1.66 | 1.18 | 17.46 | 6.55 | 24.30 | 39.47 | 0.06 |
| Total Mean    |       | 12.78 | 50.12 | 22.87 | 9.69 | 17.15 | 120.75 | 245.19 | 241.69 | 12.09 | 12.32 | 0.00 | 11.05 | 0.06 | 1.58 | 2.93 | 40.03 | 4.78 | 11.39 | 79.90 | 9.11 |
|              | SD    | 5.18  | 11.03 | 6.95 | 5.59 | 4.52 | 36.95 | 107.14 | 68.98 | 4.06 | 5.16 | 0.00 | 3.26 | 0.08 | 0.84 | 0.96 | 13.39 | 0.48 | 1.21 | 26.02 | 2.88 |

The data set is for 14 OPEC countries covering the period of 1971 to 2017; hence, the total is for the 14 OPEC countries as a group. Y_1, Y_2, Y_3, Y_4, Y_5, and Y_6 are the sector’s value added (representing the economic output) for mining, manufacturing, construction, transport, agriculture and commercial sectors, respectively; Y_7 is the household consumption expenditure (representing the residential income); and Y is the real GDP (representing the total economic output).

E_1, E_2, E_3, E_4, E_5, E_6, E_7 and E are the energy use (in Mtoe) for mining, manufacturing, construction, transport, agriculture, commercial, residential and aggregate sectors, respectively.

CO2 is CO₂ emissions tonne per capita; TO is trade openness proxy by trade (import plus export) as a % share of GDP; ES is cleaner energy substitute proxy by renewable energy as a % share of energy use.
| Country     | Indices | Average indices (1971 = 1) | Changes in indices (%) | Energy savings (Ktoe) | Contribution to saving (%) |
|------------|---------|---------------------------|-------------------------|----------------------|--------------------------|
| Algeria    | EI      | 1.43 2.50 2.55 2.77       | 0.11 0.05 -0.04 0.05    | -2.50 -10.61 -14.07  -24.40 | 1.00 1.00 1.00 1.00       |
|            | Efficiency | 1.33 2.29 2.42 2.45       | 0.09 0.05 -0.03 0.02    | -2.09 -9.56 -13.31  -21.44 | 0.69 0.90 0.95 0.88       |
|            | Structure | 1.07 1.10 1.05 1.13       | 0.01 0.00 0.00 0.01    | -0.41 -1.05 -0.75  -2.96   | 0.31 0.10 0.05 0.12       |
| Angola     | EI      | 1.10 1.33 1.26 0.92       | 0.02 0.05 -0.08 -0.01   | -0.31 -1.01 -1.04  0.89    | 1.00 1.00 1.00 1.00       |
|            | Efficiency | 1.08 1.62 1.80 1.19       | 0.01 0.14 -0.12 -0.04   | -0.26 -1.55 -2.76  -1.53   | 0.76 1.28 0.61 -2.60      |
|            | Structure | 1.01 0.91 0.72 0.78       | 0.01 -0.04 0.00 0.02    | -0.05 0.54 1.73  2.43     | 0.24 -0.28 0.39 3.60      |
| Ecuador    | EI      | 0.86 0.57 0.50 0.78       | -0.04 0.00 0.01 0.03    | 0.11 0.46 0.64  0.46     | 1.00 1.00 1.00 1.00       |
|            | Efficiency | 0.90 0.61 0.49 1.03       | -0.03 -0.01 0.01 0.05   | 0.08 0.40 0.67  0.01     | -1.54 0.88 1.04 -0.88     |
| Gabon      | EI      | 0.96 0.94 1.03 0.86       | -0.01 0.01 0.00 -0.01   | 0.03 0.06 -0.03 0.45      | 2.54 0.12 -0.04 1.88      |
|            | Structure | 0.96 0.94 1.03 0.86       | -0.01 0.01 0.00 -0.01   | 0.03 0.06 -0.03 0.45      | 2.54 0.12 -0.04 1.88      |
| IR Iran    | EI      | 0.83 0.86 1.08 2.15       | -0.00 -0.02 0.10 0.02   | 0.24 0.19 -0.14 2.32      | 1.00 1.00 1.00 1.00       |
|            | Efficiency | 0.92 0.86 1.05 1.42       | 0.00 -0.01 0.05 0.02    | 0.09 0.19 -0.11 1.04      | 0.45 0.66 0.47 0.44       |
|            | Structure | 0.89 1.00 1.01 1.51       | 0.00 -0.01 0.03 0.03    | 0.15 0.01 -0.03 1.28      | 0.55 0.34 0.53 0.56       |
| Iraq       | EI      | 1.56 3.42 4.65 5.39       | 0.11 0.19 0.06 0.01    | -9.46 -39.49 -87.65 -152.47 | 1.00 1.00 1.00 1.00       |
|            | Efficiency | 1.08 1.71 2.12 2.23       | 0.02 0.07 0.01 -0.01   | -1.65 -17.38 -42.78 -72.47 | 0.22 0.43 0.49 0.47       |
|            | Structure | 1.41 1.99 2.20 2.42       | 0.07 0.03 0.01 0.02    | -7.81 -22.12 -44.87 -80.00 | 0.78 0.57 0.51 0.53       |
| Kuwait     | EI      | 1.21 3.26 2.85 1.82       | 0.06 0.27 -0.24 0.04   | -1.21 -9.40 -11.95 -11.12 | 1.00 1.00 1.00 1.00       |
|            | Efficiency | 1.20 2.28 1.96 1.74       | 0.04 0.12 -0.09 0.03   | -1.09 -6.74 -7.89 -10.28  | 1.72 0.73 0.66 0.91       |
|            | Structure | 1.01 1.37 1.42 1.05       | 0.02 0.05 -0.05 0.00   | -0.12 -2.66 -4.06 -0.84   | -0.72 0.27 0.34 0.09      |
| Libya      | EI      | 1.73 3.25 2.50 2.70       | 0.22 -0.08 -0.02 0.08  | -2.57 -6.90 -7.82 -14.34  | 1.00 1.00 1.00 1.00       |
|            | Efficiency | 1.04 1.49 1.34 1.20       | 0.03 0.00 -0.03 0.02   | -0.20 -2.47 -2.44 -2.66   | 0.04 0.31 0.32 0.17       |
|            | Structure | 1.42 3.65 4.18 8.34       | 0.13 0.15 -0.09 0.96   | -1.18 -6.26 -8.91 -8.78   | 1.00 1.00 1.00 1.00       |
| Nigeria    | EI      | 1.37 3.05 2.93 6.16       | 0.10 0.11 -0.13 0.77   | -1.06 -5.38 -6.62 -7.15   | 0.96 0.86 0.74 0.83       |
|            | Efficiency | 1.03 1.20 1.44 1.38       | 0.01 0.00 0.04 -0.03   | -0.12 -0.88 -2.29 -1.63   | 0.04 0.14 0.26 0.17       |
|            | Structure | 0.98 1.34 1.30 0.89       | 0.02 0.01 0.03 -0.02   | 1.10 -15.12 -17.89 15.66  | 1.00 1.00 1.00 1.00       |
| Qatar      | EI      | 0.99 1.55 1.28 0.83       | 0.02 0.03 -0.05 0.01   | 0.28 -22.30 -14.41 23.73  | 2.54 1.48 0.65 -33.99      |
|            | Efficiency | 0.99 0.87 1.04 1.07       | 0.00 -0.01 0.01 0.00   | 0.82 7.18 3.47 8.07       | -1.54 -0.48 0.35 34.99     |
|            | Structure | 2.25 6.23 5.94 4.46       | 0.40 0.11 -0.11 -0.10  | -0.94 -4.11 -8.23 -20.42  | 1.00 1.00 1.00 1.00       |
| Saudi Arabia | EI    | 2.15 4.59 5.22 4.03       | 0.36 0.01 0.00 -0.10   | -0.89 -3.42 -7.63 -18.95  | 1.14 0.83 0.93 0.93       |
Table A8  Continued

| Country | Indices | Average indices (1971 = 1) | Changes in indices (%) | Energy savings (Ktoe) | Contribution to saving (%) |
|---------|---------|----------------------------|-------------------------|-----------------------|--------------------------|
|         |         | 1971 | 1982 | 1994 | 2006 | 2017 | 1971 | 1982 | 1994 | 2006 | 2017 | 1971 | 1982 | 1994 | 2006 | 2017 | 1971 | 1982 | 1994 | 2006 | 2017 | 1971 | 1982 | 1994 | 2006 | 2017 |
| Efficiency | 1.05 | 1.36 | 1.14 | 1.11 | 0.01 | 0.02 | -0.02 | 0.00 | -0.05 | -0.69 | -0.60 | -1.47 | -0.14 | 0.17 | 0.07 | 0.07 |
| Structure | 1.93 | 6.12 | 7.31 | 8.76 | 0.37 | 0.10 | 0.13 | 0.06 | -8.76 | -37.41 | -65.59 | -122.26 | 1.00 | 1.00 | 1.00 | 1.00 |
| UAE | 2.02 | 4.69 | 5.31 | 4.58 | 0.34 | -0.01 | 0.05 | -0.08 | -9.44 | -31.88 | -54.97 | -85.36 | 1.24 | 0.85 | 0.84 | 0.70 |
| Structure | 0.94 | 1.31 | 1.37 | 1.92 | 0.01 | 0.02 | 0.01 | 0.04 | 0.68 | -5.53 | -10.62 | -36.90 | -0.24 | 0.15 | 0.16 | 0.30 |
| Venezuela | 1.47 | 5.02 | 4.74 | 5.30 | 0.14 | 0.25 | -0.15 | 0.13 | -1.49 | -12.17 | -20.63 | -40.10 | 1.00 | 1.00 | 1.00 | 1.00 |
| Structure | 0.97 | 1.30 | 1.05 | 1.13 | -0.02 | 0.05 | -0.05 | 0.03 | 0.23 | -2.08 | -0.18 | -2.90 | 0.91 | 0.13 | 0.01 | 0.07 |
| Efficiency | 1.60 | 3.83 | 4.56 | 4.71 | 0.20 | 0.06 | 0.04 | 0.01 | -1.72 | -10.09 | -20.45 | -37.20 | 0.09 | 0.87 | 0.99 | 0.93 |
| Structure | 1.04 | 1.28 | 1.46 | 1.25 | 0.02 | 0.02 | -0.01 | 0.00 | -0.91 | -7.54 | -15.05 | -10.90 | 1.00 | 1.00 | 1.00 | 1.00 |