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How Significant is Energy Efficiency to Mitigate CO₂ Emissions? Evidence from OECD Countries

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Abstract

This paper develops a two-step approach to investigate the effect of energy efficiency improvements on CO₂ emissions at the macro level. We use the index decomposition analysis to derive the true energy efficiency by separating out the impact of structural shifts in economic activity on energy intensity. We then employ both STSM and LSDVC models to examine and quantify the impact of the energy efficiency on CO₂ emissions accounting for non-economic factors such as consumers' lifestyle, attitudes and environmental awareness. The application for 30 OECD countries shows that at the group level, the decline in energy intensity predominately occurred due to improvements in energy efficiency while at the country level, there are mixed contributions from improvement in energy efficiency and structural shift to the decline in energy intensity. The econometric results show that income has the most significant positive impact on CO₂ emissions but improving energy efficiency makes the biggest contribution to driving down CO₂ emissions. The method further enables the separate assessment of non-economic behavioural effects, which are found to exert a non-trivial influence on CO₂ emissions in parallel with changes in energy efficiency. We conclude that energy efficiency remains a key option but that there is also a need for additional policies aiming for behavioural and other non-economic changes.

Keywords: Energy efficiency; Index decomposition analysis; STSM, bias-corrected LSDV; CO₂ emissions; OECD

JEL codes: C22, Q41, Q43

1. Introduction

Economic growth and energy consumption move in tandem with externality problems at both local and global scales. Understanding how to save energy and reduce CO₂ emissions is critical for global climate change policies and for providing insights how emerging economies may develop a low emission future.

In general, a country's energy demand changes over time for a variety of reasons: growth in economic output, changes in the structure of production and consumption and in trade structure, efficiency improvements and investments in infrastructure. A key method for understanding the relative contribution of each of these factors to changes in energy demand is decomposition analysis (Boyd *et al.*, 1987; Metcalf, 2008). Existing studies have applied different decomposition techniques to disentangle the impact of a structural shift in economic activity (economic activity index) from the reductions in energy use (energy efficiency index). The resulting energy efficiency index, generally referred to as the 'true' or 'sectoral' energy efficiency, reflects the true energy use per unit of economic output (see e.g. Boyd and Roop, 2004; Choi and Ang, 2003; Inglesi-Lotz and Pouris, 2012 and Zhao *et al.*, 2010).

Index number decomposition studies provide a reliable measure of energy efficiency, and give clarity regarding which determinant (true efficiency index or activity index) has been more important in driving the improvement in energy intensity (see Liu and Ang, 2007 for a survey). It is also safe to conclude from this literature that in the last three decades of the 20th century trends in aggregate energy intensity have been influenced more by energy efficiency change than by changes in the production structure despite differences in data, specific method, scope and sector in the numerous decomposition studies (Mulder, 2015).

While decomposition studies are useful for understanding trends in energy use, they provide limited insight into the effects of energy efficiency and structural shifts in economic activity on a country's level of CO₂ emissions. The analysis of macro-economic determinants of pollutant emissions has developed separately, usually with reference to the Environmental Kuznets Curve (EKC) hypothesis and the environment, economy and energy (3E) nexus (Ang, 2007; Grossman and Krueger, 1991; Soytaş *et al.*, 2007). The application to CO₂ emissions spurred a considerable volume of literature (see e.g., Acaravci and Ozturk, 2010; Dinda, 2004; Pao and Tsai, 2011; Sari and Soytaş, 2009; Stern 2004). These studies, however, do not explicitly consider the impact of energy efficiency on CO₂ emissions. Some existing studies interpret their results within the context of income, efficiency and composition effects but they rarely provide separate estimates for the magnitudes of these effects (Antweiler *et al.*, 2001). Consequently, there is a research void with regard to both the

analytics and the empirics of the extent in which energy efficiency improvement can help mitigate CO₂ emissions at the macro level. An improved understanding is also of practical importance. Energy efficiency improvement is one of the most cost-effective and most readily scalable options to support sustainable growth and reduce further damage to the climate system and world governments are encouraged to exploit it as a first choice in their energy strategy (e.g., EGEE, 2007).

Our paper contributes to the literature in several ways. Firstly, we integrate insight from two strands of literature; one strand on index number decomposition and another strand on energy and environmental economics on the EKC and the energy-income nexus. Based on these insights we propose a two-step empirical approach to allow for an improved empirical understanding of the impact of energy efficiency on CO₂ emissions at country and group levels. In the first step, we undertake detailed energy intensity decomposition to separate the contribution of fundamental improvements in energy efficiency and structural shifts in economic activity to changes in energy intensity. To accomplish this, we employ an index decomposition analysis (IDA) based on the Fisher Ideal Index (Fisher, 1921). In the second step, we use econometric models of a modified dynamic 3E framework to analyse the impact of the energy efficiency and structural shifts on CO₂ emissions controlling for other factors.

Secondly, in order to explore significant heterogeneity among countries, our study employs both structural time series modelling (STSM) developed by Harvey (1989) and panel data modelling, the bias-corrected least square dummy variable (LSDVC) estimator in the second step. Countries are likely to possess (substantial) peculiarity in terms of energy efficiency developments and panel data alone may not appropriately account for the possible energy efficiency heterogeneity among the countries. This may hinder proper inference with regards to the impact of energy efficiency improvement on CO₂ emissions. The choice of data approach is also a major source of contention among studies that have examined the EKC hypothesis and the 3E nexus, especially studies that have focused on a group of countries. The different choices may partly account for the inconsistency of the results in the existing literature. Therefore, combining both time series and panel data methods in the same study could offer advantages over a single method, by minimising variations in results and ensuring more reliable policy recommendations.

Thirdly, our approach offers further improvement on the existing literature by clearly indicating not only the impact of key economic drivers on CO₂ emissions, but also the impact of exogenous noneconomic factors (ExNEF) such as consumers' tastes, lifestyle, values and preferences, increasing desire and attitude to protect the environment factors. This follows

from the growing call and attempt to consider the impact of noneconomic factors for a better and clearer understanding of future sustainable consumption and CO₂ emissions emanating from energy consumption. Moreover, it has been underscored in a separate strand of literature that the noneconomic factors would be likely to have a significant influence on energy demand and hence, on CO₂ emissions (see e.g. Chitnis and Hunt, 2012; Martiskainen, 2008). The STSM allows for the estimation of a stochastic rather than a deterministic underlying carbon emissions trend (UCET).⁴ The UCET is likely to be strongly affected by changes in technology and energy efficiency (if there are no proxies for them in the model) and ExNEF factors, which are not easily measured, but could be influencing CO₂ emissions. To the authors' knowledge, there are no such stochastic components developed into a panel data model. Consequently, we follow Adeyemi *et al.* (2010), Adeyemi and Hunt (2007) and Griffin and Schulman (2005) submission to use time dummies in a panel data model such as the bias-corrected LSDV to effectively capture technical change and other ExNEF.

Lastly, the further aim of this paper is attempt to quantify the relative contributions of the drivers (including ExNEF) of annual changes in CO₂ emissions using the preferred models from the econometrics analysis. Some other studies have instead applied decomposition techniques directly to CO₂ emissions (or CO₂ intensity) to obtain the income, technique (efficiency) and composition (structural) contributions (see e.g. Diakoulaki *et al.*, 2006; Hatzigeorgiou *et al.*, 2008). Although these are worthy early attempts, the approach is purely descriptive. It requires large amount of data and is restrictive concerning the quantification of the contribution of technical progress and behavioural factors (such as ExNEF) to changes in CO₂ emissions. Our study, which combines both decomposition and econometric approaches, improves on these earlier attempts.

As far as we know, this study is the first to use these approaches to estimate and quantify the impacts of energy efficiency on CO₂ emissions controlling for other key factors including the ExNEF. Through the empirical assessment undertaken, therefore, the three following sub-questions are addressed. What is the true level of energy efficiency across countries? Do energy efficiency and economic factors have long term effects on CO₂ emissions when accounting for non-economic factors? To what extent does energy efficiency mitigate the level of CO₂ emissions?

We illustrate our approach and answer the questions for the case of the Organization for Economic Co-operation and Development (OECD) and our application is for 1971-2013.

⁴ Studies that adopt STSM for analysing energy demand models named the stochastic trend as underlying energy demand trend (UEDT) (see e.g. Adeyemi *et al.*, 2010; Hunt *et al.*, 2003). Accordingly, we refer to it as underlying carbon emission trend (UCET).

A number of factors make OECD countries relevant for this study. Almost all OECD countries belong to Annex I parties under the Kyoto protocol with legally binding targets for CO₂ emissions reduction⁵ and they have signed to the Paris agreement on the reduction of climate change.⁶ Moreover, there has been a downward trend in the OECD energy intensity index (see World Bank, 2016). Analysing the main drivers of the changes in energy intensity and the impact of these drivers on CO₂ emissions will be instructive for energy policymaker aiming to improve the environmental sustainability of energy use.

We continue as follows. Sections 2 and 3 present the methodology and data sources respectively. The empirical results are in section 4. Section 5 offers concluding remarks.

2. Methodology

This section gives details of a two-step estimation procedure used in this study. The first step uses an index decomposition analysis based on the Fisher Ideal index to decompose the changes in energy intensity index into structural shift index and energy efficiency index. The second step uses both time series and panel data econometric models of a modified 3E framework to determine and quantify the impact of energy efficiency improvement on CO₂ emissions in the light of the economic and other exogenous noneconomic factors.

2.1. Energy intensity decomposition analysis

Several decomposition methods have served as useful tools for identifying the contributions from different underlying factors to changes in energy intensity. Hoekstra and Van der Berg (2003) distinguished these methods in two categories – the structural decomposition analysis (SDA) and the index decomposition analysis (IDA). The SDA makes use of the input-output method to decompose improvements in energy intensity, whereas IDA (also known as the disaggregation technique) can be applied to data available at any level of aggregation or/and available in time series format. In other words, the major difference between these two methods is the type of data that are used. Although SDA has a major advantage over IDA for distinguishing indirect effects, such as technical effects, from direct effects, it requires more disaggregated data. Owing to the lack of energy data in an input-output format, researchers often use the IDA methods (Inglesi-Lotz and Pouris, 2012).

⁵ The Kyoto protocol targets commit developed countries (as a group) to curb domestic emissions by 5% relative to the 1990 level in the 1st commitment period 2008 - 2012. A second commitment period, the Doha Amendment to the Kyoto protocol, was agreed on in 2012 and parties committed to reduce GHG emissions by at least 18% below 1990 levels in the 8 years period 2013-2020 but the composition of parties in the second commitment period is different from the first. (UNFCCC, available at: www.unfccc.int).

⁶ The Paris Agreement (PA), starting in the year 2020, aims to strengthen the global response to the threat of climate change 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. The PA went into effect on 4 November 2016 after the threshold for entry into force was achieved on 5 October 2016. As of March 2017, 194 members have signed the treaty, 143 of which have ratified it (UNFCCC, available at: www.unfccc.int).

Within the IDA approach, the Fisher Ideal Index (Fisher, 1921) and Logarithmic Average Divisia Index (LMDI) are usually preferred for their desirable properties such as the ability to give perfect 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). Following Metcalf (2008), this study decomposes energy intensity using IDA that is based on the Fisher Ideal Index (FII) as follows.

Denoting E_t as the total energy consumption; Y_t as the total output; E_{it} and Y_{it} are the total energy consumption and measure of economic activity (e.g. value added to output) for sector i in year t respectively. Aggregate energy intensity (e_t) can be written as the weighted average of sectoral energy intensity, where weights are output share of the sectors. Explicitly,

$$e_t = \frac{E_t}{Y_t} = \sum_i \left(\frac{E_{it}}{Y_{it}} \right) \left(\frac{Y_{it}}{Y_t} \right) = \sum_i e_{it} s_{it} \quad (1)$$

Eq. (1) shows that aggregate energy intensity is equal to the sum of the products of energy intensity within a given sector (e_{it}) and changes in the structure of the economy (s_{it}) across sectors. 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 $I_t = e_t/e_0 = \sum_j e_{it} s_{it} / \sum_j e_0 s_{i0}$.

Following Diewert (2001), if we can distinguish sectors that account for all of the energy use in the economy (without overlap) and there exists a set of economic activities measures (Y_{it}) with which to create a measure of sectoral energy intensity (e_{it}), then we can decompose the energy intensity index (I_t) into an efficiency index (D_t^{EFF}) and an activity index (D_t^{ACT}). The efficiency index therefore attributes energy intensity to efficiency change holding the economic activity constant, and the activity index attributes energy intensity to structural changes in economic activities holding efficiency within a sector constant (Moshiri and Duah, 2016). Specifically,

$$I_t = \frac{e_t}{e_0} = D_t^{EFF} \times D_t^{ACT} \quad (2)$$

To arrive at the decomposed intensity index (Eq. 2), the below Laspeyres and Paasche indices that use a base period fixed weight and an end period fixed weight respectively can be used.

$$\text{Laspeyres: } L_t^{EFF} = \frac{\sum_i e_{it} s_{i0}}{\sum_i e_{i0} s_{i0}}; L_t^{ACT} = \frac{\sum_i e_{i0} s_{it}}{\sum_i e_{i0} s_{i0}}; \text{Paasche: } P_t^{EFF} = \frac{\sum_i e_{it} s_{it}}{\sum_i e_{i0} s_{it}}; P_t^{ACT} = \frac{\sum_i e_{it} s_{it}}{\sum_i e_{it} s_{i0}}$$

The two indices however might give different decompositions as they use different base year (Moshiri and Duah, 2016) and/or give residual terms which could account for a considerable degree of the variability in the underlying index of energy intensity change (Metcalf, 2008).

The Fisher Ideal Index (Fisher, 1921) and Log Mean Divisia index (Ang, 2004) are developed to overcome the underlined setbacks by decomposing the energy intensity perfectly into an efficiency index and activity index with no unexplained residuals. Specifically, the Fisher Ideal Index uses the weighted average of the Laspeyres and Paasche indices to derive the efficiency index F_t^{EFF} and activity index F_t^{ACT} as follows:

$$F_t^{EFF} = (L_t^{EFF} \times P_t^{EFF})^{1/2}; \quad F_t^{ACT} = (L_t^{ACT} \times P_t^{ACT})^{1/2}$$

As in Eq. (2), the energy intensity index is then given as the product of the two indices as:⁷

$$I_t = \frac{e_t}{e_0} = F_t^{EFF} \times F_t^{ACT} \quad (3)$$

Using Eq. (3) and denoting energy savings (ΔES_t) in year t due to an improvement in energy intensity as $\Delta ES_t = E_t - \hat{E}_t$, we can also separate changes in energy savings resulting from improvements in energy efficiency and structural shifts in the economy as:

$$\Delta ES_t = \Delta ES_t \left(\frac{\ln(F_t^{EFF})}{\ln(I_t)} \right) + \Delta ES_t \left(\frac{\ln(F_t^{ACT})}{\ln(I_t)} \right) = \Delta ES_t^{EFF} + \Delta ES_t^{ACT} \quad (4)$$

where E_t is the actual energy use and $\hat{E}_t$ is the energy that would have been used had energy intensity remained at a base-year level.

Using more disaggregated data that accounts for all of the likely changes in economic activities helps to improve the reliability of the decomposition analysis. Many studies that have applied this method, however, are constrained by data limitations.⁸ This study will decompose along 7 key sectors – mining, manufacturing, construction, transport, agriculture, commercial, and residential that account for all of the energy use in the OECD countries with average shares of 11.5%, 30.5%, 0.7%, 23.7, 3%, 9.9% and 20.8% respectively.

2.2. Determinants of the changes in CO₂ emissions

The decomposition analysis above is purely a descriptive exercise. Although it shows how energy intensity has changed over time and the share of the changes attributed to energy efficiency improvements, it does not show the impact of the efficiency improvement on CO₂ emissions. To study this impact, we next present an analysis of the impact of the decomposed indexes on CO₂ emissions, exploring the link between (energy demand and efficiency) and (energy demand and emissions) in a time series and panel data framework.

⁷ Similarly, the Log Mean Divisia Index uses a log mean weight function to derive the efficiency L_t^{EFF} and activity L_t^{ACT} indices as $L_t^{EFF} = \exp[\sum_i \langle L(\frac{E_{it}}{Y_t}, \frac{E_{it}}{Y_0}) / L(e_t, e_0) \rangle \ln(\frac{e_{it}}{e_{i0}})]$ and $L_t^{ACT} = \exp[\sum_i \langle L(\frac{E_{it}}{Y_t}, \frac{E_{it}}{Y_0}) / L(e_t, e_0) \rangle \ln(\frac{s_{it}}{s_{i0}})]$ respectively, where function $L(a, b)$ is the logarithmic average of two positive numbers a and b given by the expression: $L(a, b) = \begin{cases} a - b / (\ln a - \ln b), & \text{if } a \neq b \\ a, & \text{if } a = b \end{cases}$

⁸ E.g., Metcalf (2008) and Oseni (2011) decomposed along 4 sectors for 46 US states and 16 OECD countries respectively; Moshiri and Duah (2016) decomposed along 7 sectors for 10 Canadian provinces.

2.2.1. Time series model

The link between energy efficiency and energy consumption can be established directly but the link between energy efficiency and CO₂ emissions can only be mediated through changes in energy consumption. Thus, we derive the framework for analysing the impact of energy efficiency improvements on CO₂ emissions by combining the two following links.

First, following Adetutu *et al.* (2016) and Broadstock and Hunt (2010) energy use is presented as a direct dependant on energy efficiency controlling for other variables as:

$$E_t = \pi_0 + \pi_1 EFF_t + \pi_2 Y_t + \boldsymbol{\tau}' \mathbf{Z}_t + \varepsilon_t \quad (5)$$

where E_t is energy use per capita; EFF_t is the measure of energy efficiency; Y_t is income per capita, $\mathbf{Z}_t$ is a vector consisting of other relevant covariates and ε_t is the error term.

Secondly, CO₂ emissions is presented as a direct dependant on energy use following Ang (2007), which combined the EKC and energy-income hypotheses to achieve the multivariate (3E) framework that facilitates the study of the link between CO₂ emissions, energy use and economic growth as follows:⁹

$$CO2_t = \vartheta_0 + \vartheta_1 Y_t + \vartheta_2 Y_t^2 + \vartheta_3 E_t + \varepsilon_t \quad (6)$$

where $CO2_t$ is CO₂ emission per capita; Y_t^2 is the square of income per capita and other variables are as defined in Eq. (5). Extant studies use ϑ_1 and ϑ_2 to test for the EKC hypothesis and if the hypothesis holds, they give interpretations in terms of efficiency and composition impacts without actually providing estimates for these components. Arguably, increases in income only necessarily translate to environmental improvements if channelled to improve energy efficiency and/or when spent on more environmentally friendly energy sources. A better approach to estimating the actual impacts of income improvements on the environment would be to get a true measure of actual energy used per economic output (i.e. the measure for energy efficiency). We could then examine the effect on CO₂ emissions rather than relying on the income threshold as captured by the estimate of ϑ_2 in Eq. (6).

Based on the above and the exposition from section (2.1), we derive a model for analysing the impact of energy efficiency improvement from domestic output on CO₂ emissions by substituting Eq. (5) in Eq. (6) to arrive at the following:

$$CO2_t = \phi_0 + \alpha_0 Y_t + \beta_0 EFF_t + \gamma_0 EFF_t^2 + \varphi_0 ACT_t + \Phi_0 ACT_t^2 + \psi_0 CES_t + \omega_0 TO_t + \varepsilon_t \quad (7)$$

where EFF_t is proxied by the energy efficiency index derived from IDA in subsection 2.1.

⁹ Some of the extant studies that have empirically estimated the 3E framework include: Acaravci and Ozturk (2010) for 19 European countries; Apergis and Payne (2010) for 11 Commonwealth Independent States; Hatzigeorgiou *et al.* (2011) for Greece; Iwata *et al.* (2010) for 11 OECD countries; Saboori and Sulaiman (2013) for 5 Association of Southeast Asian Nations; Soytaş *et al.* (2007) for U.S.

Consistent with some of existing studies on the 3E nexus, we control for the impact of changes in structural composition of the economy, cleaner energy substitution and openness of the economy to trade captured by ACT_t , CES_t and TO_t respectively to avoid omission bias.¹⁰ Moreover, the relationship between CO₂ emissions and energy efficiency may be non-linear. Countries that are energy inefficient may improve over time and become more efficient. There could also be a declining return to improving energy efficiency (in terms of smaller marginal reductions in CO₂ emissions over time), which would mean a nonlinear effect. Thus, we hypothesized that the nonlinear effect is *a-priori* ambiguous and can be determined empirically by adding the squared term of the energy efficiency index EFF_t^2 in the model.¹¹ We use a similar analogy to include the squared term of the activity index ACT_t^2 .

Eq. (7) is a static model and as such, it assumes the response of CO₂ emissions to changes in any of the explanatory variables to be immediate. In reality, CO₂ emissions may require some time to adjust to improvements in energy efficiency or shifts in the composition of the economy. Similarly, the previous level of CO₂ emissions may instigate stringent policy to mitigate future CO₂ emissions and the erstwhile energy efficiency achieved may have spill over effects on subsequent CO₂ emissions. In this context, we adopt a dynamic model, starting with two-lagged dependent and independent variables, i.e. $ARDL(2, 2)$.¹²

Lastly, we introduce an underlying carbon emissions trend (UCET) μ_t into the model. Also note that in Eq. (7) we separate out the effect of technical progress and energy efficiency from the UCET by incorporating an appropriate proxy variable for energy efficiency. Arguably, the estimated UCET, which could be stochastic or deterministic, should thus only pick up the effects of other noneconomic factors; hence, it is assumed to capture the effect of exogenous changes in such factors as societal preferences, lifestyle, values, attitudes and peoples' environmental awareness (see Broadstock and Hunt, 2010; Chitnis and Hunt, 2012). Considering all these factors together, we therefore restate Eq. (7) as follows:

$$\begin{aligned} co2_t = & \mu_t + \sum_{j=0}^2 \alpha_j y_{t-j} + \sum_{j=0}^2 \beta_j eff_{t-j} + \sum_{j=0}^2 \gamma_j eff_{t-j}^2 + \sum_{j=0}^2 \varphi_j act_{t-j} + \sum_{j=0}^2 \Phi_j act_{t-j}^2 \\ & + \sum_{j=0}^2 \psi_j CES_{t-j} + \sum_{j=0}^2 \omega_j TO_{t-j} + \sum_{j=1}^2 \lambda_j co2_{t-j} + \varepsilon_t \end{aligned} \quad (8)$$

¹⁰ We proxy changes in the structural composition of the economy by activity index derived from Eq. (3), cleaner energy substitution by alternative and nuclear energy as % of total energy use (see also footnote 22) and trade openness by trade (export + import) as % of GDP.

¹¹ It follows that, if a country is having a declining energy efficiency index and we found $\beta_0 > 0$ and $\gamma_0 < 0$ in Eq. (7), then energy efficiency index forms a U-shape relationship with CO₂ emissions after a given minimum. In contrast, if the country is having an increasing energy efficiency index and we found $\beta_0 > 0$ and $\gamma_0 < 0$, then the non-linear effect forms an inverted U-shape after a given threshold.

¹² Given the length of our data, the lags are limited to two to avoid losing many degrees of freedom.

All the variables are in natural log, with the exception of the cleaner energy substitution and trade openness, which are in percentages.

With Eq. (8), the short- and long- run elasticities of the regressors with respect to CO₂ emissions can be estimated together.¹³ However, with the introduction of the unobservable component μ_t , if it is found to be stochastic, it will render common estimators such as OLS biased and inconsistent. The structural time series model (STSM) developed by Harvey (1989) helps to overcome this problem. The STSM combined with ARDL is simple to comprehend. The order of integration of the variables is not very crucial for STSM and allows the trend component μ_t in the model to vary stochastically over time (Amarawickrama and Hunt, 2008).

With the STSM, the trend μ_t is assumed to have the following stochastic process:

$$\mu_t = \mu_{t-1} + \varrho_{t-1} + \eta_t \quad \eta_t \sim NID(0, \sigma_\eta^2) \quad (9)$$

$$\varrho_t = \varrho_{t-1} + \xi_t \quad \xi_t \sim NID(0, \sigma_\xi^2) \quad (10)$$

The trend includes a level (Eq. 9), defined as the trend in past period plus a growth term; a slope (Eq. 10) generated by a random walk; η_t and ξ_t are white noise disturbance term.¹⁴ The hyperparameters (i.e., σ_η^2 and σ_ξ^2) values determine the nature of the stochastic trend. Thus, this gives a number of alternative forms of the stochastic trend and in the limiting case $\sigma_\eta^2 = \sigma_\xi^2 = 0$, the model collapses to a conventional deterministic time trend regression.¹⁵ The likelihood ratio (LR) test can be used to determine whether the hyperparameters are actually equal to zero.¹⁶ Also the inclusion of irregular, level and slope interventions in μ_t gives information about possible structural breaks at certain periods of the estimation (Harvey and Koopman, 1992; Hunt *et al.*, 2003, Broadstock and Hunt, 2010).¹⁷

The Maximum Likelihood procedure in conjunction with the Kalman filter is used to estimate the general STSM-ARDL (2, 2) function, consisting of Eqs (8) - (10) in STAMP 8.2 software (Koopman *et al.*, 2009). The general model is considered initially and the preferred parsimonious specification of the model found by testing down and eliminating insignificant variables while ensuring that the model passes a range of diagnostic tests.

¹³ E.g., the short- and long-run income elasticities are given as α_0 and $\sum_{j=0}^2 \alpha_j / (1 - \sum_{j=1}^2 \lambda_j)$ respectively

¹⁴ An important assumption for these models is that the three error terms ε_t , η_t and ξ_t are independent and uncorrelated.

¹⁵ I.e., the UCET component in Eq. (8) collapses to $\mu_t = \phi_0 + bt$; where ϕ_0 is the constant in Eq. (7) and t is a linear time trend

¹⁶ Given that the restriction is on the hyper-parameters, an LR test expressed as $LR(r) = -2(LL_R - LL_U) \sim \chi_r^2$ is suitable to test the validity of the restriction. 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 hyper-parameters.

¹⁷ The UCET in this case is given as $UCET = \mu_t + \text{level interventions} + \text{slope interventions} + \text{irregular interventions}$. If none of the interventions are significant then $UCET = \mu_t$.

2.2.2 Panel data model

Using exposition similar to that for deriving the time series model Eq. (7), we present the panel data model as follows:

$$co2_{nt} = \phi_0 + \alpha_0 y_{nt} + \beta_0 eff_{nt} + \gamma_0 eff_{nt}^2 + \varphi_0 act_{nt} + \Phi_0 act_{nt}^2 + \psi_0 CES_{nt} + \omega_0 TO_{nt} + \theta_t D_t + u_{nt} \quad (11)$$

where $n = 1, 2, \dots, N$ is each country in the panel; $t = 1, 2, \dots, T$ refers to the period; the composite error $u_{nt} = v_n + \Omega_{nt}$ where v_n is the unobservable country-specific effects; Ω_{nt} is the idiosyncratic error term and the definitions of other variables are as above.

Several facts are noteworthy of Eq. (11). First, as mentioned in Section 1, we include time dummies D_t to capture the impact of ExNEF in line with Adeyemi *et al.* (2010), Adeyemi and Hunt (2007) and Griffin and Schulman (2005) that time dummies are a good proxy for ExNEF in a panel model. Secondly, since $co2_{it}$ is a function of v_n , which is time invariant, it follows that the inclusion of $co2_{nt-1}$ as one of the regressors in Eq. (11) will correlate with u_{nt} which contains v_n rendering an ordinary least square (OLS) biased and inconsistent. The fixed effect or least square dummy variable (LSDV) estimator which eliminates v_n through within transformation does not completely solve the problem.¹⁸

A common method to solve this problem is to take the first difference of Eq. (11) to eliminate v_n via either an instrumental variable approach (e.g., Anderson and Hsiao, 1982) or a generalized method of moments (GMM) estimator (e.g., Arellano and Bond, 1991; Arellano and Bover, 1995; Blundell and Bover, 1998). However, the basic properties of GMM estimators hold for small T , large N panels. The number of instruments in GMM tends to explode with T and biases the estimates towards those of the OLS (Roodman, 2009). Consequently, the application of the GMM estimators to a small cross-section or large T , as in the present study, may bias the estimated parameters and standard errors.

Kiviet (1995) proposes an alternative approach 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-Hsiao and the Kiviet - corrected LSDV estimator (LSDVC) are better than the GMM estimator in this circumstance. Judson and Owen (1999) use a similar method to Kiviet (1995) 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.

¹⁸ For details of this discussion, see e.g., Baltagi (2008), Filippini (2011), Nickell (1981) and Roodman (2009).

Following the exposition from these studies and the nature of our panel data (i.e. large T and small N), our preferred estimator for the determinants of CO₂ emissions in a dynamic panel model is the LSDVC estimator. Prior to this estimation, we estimate the static model (Eq. 11) using either LSDV or RE as a benchmark for the dynamic model. Besides, since the LSDVC is designed for a dynamic panel model with one lagged-dependent variable, the dynamic version of Eq. (11) to be estimated is stated as follows:

$$co2_{nt} = \phi_0 + \alpha_0 y_{nt} + \beta_0 eff_{nt} + \gamma_0 eff_{nt}^2 + \varphi_0 act_{nt} + \Phi_0 act_{nt}^2 + \psi_0 CES_{nt} + \omega_0 TO_{nt} + \theta_t D_t + \lambda_0 co2_{nt-1} + u_{nt} \quad (12)$$

where $co2_{nt-1}$ is the first lag of CO₂ emissions, and the definitions of other variables are as in Eq. (11). The panel models specified in Eqs (11) and (12) may be prone to other econometric issues (such as endogeneity and cross-section dependence), we discuss and test for these issues in subsection 4.3. The estimations are conducted in STATA 14 software.

2.2.3. Contributions of the drivers to annual changes in CO₂ emissions

As mentioned in section 1, we aim to examine not only the link between the regressors (including energy efficiency improvements) and CO₂ emissions, but to quantify their relative contributions to the annual change in CO₂ emissions. The first aim is achieved by estimating the coefficients of Eqs (8) and (12) for the time series and panel data respectively. For the second aim, if the preferred parsimonious model does not include any lags, the relative contributions are easily calculated using the procedure in Broadstock and Hunt (2010) as:

$$\Delta \widehat{co2}_t = \Delta \hat{\mu}_t + \hat{\alpha}_0 \Delta y_t + \hat{\beta}_0^* \Delta eff_t + \hat{\varphi}_0^* \Delta act_t + \hat{\psi}_0 \Delta CES_t + \hat{\omega}_0 \Delta TO_t \quad (13)$$

where $\hat{\alpha}_0$, $\hat{\beta}_0^*$, $\hat{\varphi}_0^*$, $\hat{\psi}_0$, and $\hat{\omega}_0$ are the estimated impacts from income, efficiency, structural shift, cleaner energy substitution and openness respectively, and $\hat{\mu}_t$ is the estimated UCET.¹⁹ Thus, $\hat{\alpha}_0 \Delta y_t$, $\hat{\beta}_0^* \Delta eff_t$, $\hat{\varphi}_0^* \Delta act_t$, $\hat{\psi}_0 \Delta CES_t$, $\hat{\omega}_0 \Delta TO_t$ and $\Delta \hat{\mu}_t$ represent the estimated relative contributions to changes in CO₂ emissions from the corresponding variables respectively.²⁰

However, if the lagged terms in Eqs 8 and 12 are significant, it is tedious to calculate the relative contributions of the regressors to changes in CO₂ emissions $\Delta \widehat{co2}_t$. In this case, Chitnis and Hunt (2012) suggested that the estimated lagged-dependent variable (e.g., $\hat{A}'(L)co2_t$ for the time series; where the polynomial lag operator $\hat{A}'(L) = \hat{\lambda}_1 L + \hat{\lambda}_2 L^2$) should be continually substituted by a lagged estimated version of Eq. (8) until $\hat{A}'(L)$ is sufficiently close to zero, and hence ignorable. This may not be easy to follow through in the case on

¹⁹ Given that energy efficiency and structural shift indices are hypothesized to have nonlinear effects, the marginal impacts are calculated $\hat{\beta}_0^* = (\beta_0 + 2\gamma_0 eff_t)$ and $\hat{\varphi}_0^* = (\varphi_0 + 2\Phi_0 act_t)$ respectively.

²⁰ Given the model is in logs the change approximates the percentage change

hand. As an alternative, we estimate the long-run elasticities of the variables, which incorporate the lags in the estimated model, and use it alongside changes in the corresponding variables to arrive at their relative contributions to the changes in CO₂ emissions $\Delta \widehat{co2}_t$. For the time series model, this is stated as follows:

$$\Delta \widehat{co2}_t = \Delta \hat{\mu}_t + \hat{\alpha}^* \Delta y_t + \hat{\beta}^* \Delta eff_t + \hat{\phi}^* \Delta act_t + \hat{\psi}^* \Delta CES_t + \hat{\omega}^* \Delta TO_t \quad (14)$$

where $\hat{\alpha}^*$, $\hat{\beta}^*$, $\hat{\phi}^*$, $\hat{\psi}^*$, and $\hat{\omega}^*$ are the long-run elasticities of the explanatory variables.²¹ Thus, $\hat{\alpha}^* \Delta y_t$, $\hat{\beta}^* \Delta eff_t$, $\hat{\phi}^* \Delta act_t$, $\hat{\psi}^* \Delta CES_t$, $\hat{\omega}^* \Delta TO_t$ and $\Delta \hat{\mu}_t$ are the estimated relative contributions of income, efficiency, structural shift, cleaner energy substitution, trade openness and ExNEF respectively to the annual change in CO₂ emissions.

For the panel data model, we adopt a similar method as in Eq. (14) and focus on changes in CO₂ emissions for the aggregate countries ($\Delta \widehat{co2}_t^a$). We use $y_t^a, eff_t^a, act_t^a, CES_t^a, TO_t^a$ for the aggregate countries²² to replace the country level variables $y_t, eff_t, act_t, CES_t, TO_t$ respectively. We also use the panel long run elasticities and derive the contribution for ExNEF using $\Delta(\hat{\theta}_t/1 - \hat{\lambda}_0)$, where $(\hat{\theta}_t/1 - \hat{\lambda}_0)$ denotes the long run UCET,²³ $\hat{\theta}_t$ and $\hat{\lambda}_0$ are the coefficients of the time dummies and $co2_{nt-1}$ respectively in the panel model Eq. (12).

3. Data

For the estimations, we use annual data over the period 1971-2015 for 30 OECD countries.²⁴ The period and countries are selected based on data availability. For the energy intensity decomposition analysis, data on the whole economy output (Y) and energy consumption (E), and the sectoral output (Y_i) and energy consumption (E_i) are used. E and E_i are proxied by aggregate and sectoral energy use (in kilo tonne of oil equivalent) respectively sourced from the International Energy Agency (IEA) database. Y is represented by real GDP (at constant 2005 prices in US\$) taken from the United Nations Statistical Division (UNSD) database. For the 7 energy-consuming sectors – mining, manufacturing, construction, transport, agriculture, commercial and residential, Y_i is represented by the measure of economic output related to the underlying energy use for each sector. E.g. personal consumption expenditure (at constant 2005 prices in US\$) sourced from UNSD is considered as a key driver of residential energy

²¹The covariates LR elasticities for the time series model are $\hat{\alpha}^* = (\sum_{i=0}^2 \hat{\alpha}_i / 1 - \sum_{i=1}^2 \hat{\lambda}_i)$, $\hat{\beta}^* = (\sum_{i=0}^2 \hat{\beta}_i + 2[\sum_{i=0}^2 \hat{\gamma}_i] \overline{eff}_t / 1 - \sum_{i=1}^2 \hat{\lambda}_i)$, $\hat{\phi}^* = (\sum_{i=0}^2 \hat{\phi}_i + 2[\sum_{i=0}^2 \hat{\Phi}_i] \overline{act}_t / 1 - \sum_{i=1}^2 \hat{\lambda}_i)$, $\hat{\psi}^* = (\sum_{i=0}^2 \hat{\psi}_i / 1 - \sum_{i=1}^2 \hat{\lambda}_i)$, $\hat{\omega}^* = (\sum_{i=0}^2 \hat{\omega}_i / 1 - \sum_{i=1}^2 \hat{\lambda}_i)$

²² Since $co2_t, y_t, eff_t$ and act_t are in log, we derive $co2_t^a$ and y_t^a by aggregating the variables across the countries, divide by the combined population and then take the log; eff_t^a and act_t^a are the log of the resulting efficiency and activity indices from the decomposed energy intensity for the aggregated countries; ES_t^a and TO_t^a are the cleaner energy share and trade openness (both in %) for the combined countries.

²³ Griffin and Schulman (2005) use this method to calculate the long run UEDT in a panel data model.

²⁴ The list of the 30 OECD countries are Australia (ASL), Austria (AST), Belgium (BEL), Canada (CAN), Chile (CHI), Denmark (DEN), Finland (FIN), France (FRA), Germany (GER), Greece (GRE), Hungary (HUN), Iceland (ICE), Ireland (IRE), Israel (ISR), Italy (ITA), Japan (JAP), Korea (KOR), Luxembourg (LUX), Mexico (MEX), Netherlands (NTL), New Zealand (NZD), Norway (NOR), Poland (POL), Portugal (POR), Spain (SPA), Sweden (SWE), Switzerland (SWZ), Turkey (TUR), United Kingdom (UK), United States (US).

demand and we prefer this measure to personal income as part of the latter goes to savings, which may not have a major impact on residential energy consumption. We use the contribution of a given sector to final production, i.e. sectoral value added (at constant 2005 prices in US\$) taken from UNSD as a proxy for economic output for the remaining 6 sectors.

For the analysis of the determinants of CO₂ emissions, in addition to the energy efficiency and structural shift indices obtained from the energy intensity decomposition, we use data on CO₂ emissions in tonne per capita (*CO2*) sourced from IEA. Trade openness (TO) is proxied by trade (import + export) as % of GDP sourced from UNSD. Cleaner energy substitution (*CES*) is proxied by alternative and nuclear energy²⁵ (% of total energy use) sourced alongside population data for deriving income per capita from the World Bank database - world development indicators. The descriptive statistics of the data for the first and second step estimations are in Tables A.1 and A.2 of the Appendix respectively.

4. Empirical results

4.1. Empirical results of energy intensity decomposition

We first use the Fisher Ideal index presented by Eq. (3) to decompose the energy intensity index into efficiency and activity indices for the period of 1971-2015. The decomposition results for OECD as a group illustrated in the line graph in Fig. 1 show interesting findings. By construction in subsection 2.1, a declining energy intensity or energy efficiency or activity index from its base value is regarded as an improvement.²⁶ Intuitively we expect positive relationships between the three variables since efficiency (or activity) index attributes improvement in energy intensity index to an improving efficiency (or structural shift away from energy-intensive sectors) holding economic activity (or energy efficiency) constant.

Taking 1971 as the base year, the total energy intensity index in 2015 is 47% of its 1971 level (energy intensity index decreases by 53% between 1971 and 2015). The efficiency index and activity index are 46% and 102.3% of their 1971 levels, respectively. Energy efficiency index is the major driver of the declining energy intensity index for OECD as a group, it accounts for 104.5% of the decline in energy intensity index while change in economic activity is found driving up energy intensity index in recent time. That is, if the composition of OECD's economic activities had remained unchanged between 1971 and 2015, energy intensity would have been 46%. Likewise, if energy efficiency had remained constant at its 1971 level, energy intensity would have increased by 2.3% of its 1971 level.

²⁵ Alternative energy is non-carbohydrate energy produced without the undesirable consequences of the burning of fossil fuels, such as high carbon dioxide emissions, which is considered to be the major contributing factor of global warming. It includes hydropower, geothermal, wind and solar power, among other renewable energy (World Bank, 2015).

²⁶ Thus, improvements are used interchangeably for declining indices while deterioration is used for increasing indices.

Fig. 1: Energy indices and energy savings relative to 1971 for OECD group-level

Using Eq. (4), we allocate the total energy (dis)saved (relative to the amount that would have been consumed had energy intensity remained at its 1971 level) between energy efficiency and structural shift. Based on this approach, in 2015, roughly 112.7% of total energy use (about 4496 Mtoe) has been saved due to the decrease in OECD energy intensity. The findings attribute 103% of the 4496Mtoe of energy saved to improvements in energy efficiency while structural changes in favour of energy-intensive sectors amount to 3% energy dissaving. The area graph in Fig. 1 shows the trend of the energy saving due to improvements in energy efficiency and compositional changes over the entire period. Throughout the period under consideration, energy saving can be attributed almost entirely to improvements in energy efficiency. Structural shift contributes only a small portion of energy savings and after 2003, it starts moving in a negative direction, with energy dissaving.

The results in Fig. 1 are at group level; improving (or deteriorating) energy efficiency at a group level does not mean that all countries within the group are efficient (or 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. Table 1 provides summary results for the three energy indices across the 30 OECD countries for various intervals between 1971 and 2015. Several facts are noteworthy.

First, energy intensity and efficiency indices have been declining at 0.829% and 0.906% average annual rate respectively but were slow in 1982-92. Activity index has been increasing at a 0.118% average annual rate across OECD countries with a decline achieved in 2004-13. Second, variations in the indices across countries are rising.

Table 1: Summary statistics of energy indices for OECD country-level

Indexes	Year	Mean	S.D.	Min	Max	Coefficient of variation	Average annual change	Average annual change (cumulative)
Intensity	1971-1982	0.972	0.092	0.709	1.182	0.094	-0.881%	-0.881%
	1983-1993	0.874	0.196	0.517	1.435	0.224	-0.379%	-0.630%
	1994-2004	0.803	0.258	0.359	1.496	0.322	-0.977%	-0.746%
	2005-2015	0.684	0.251	0.266	1.407	0.367	-1.079%	-0.829%
	Total	0.837	0.233	0.266	1.496	0.279	-0.829%	
Efficiency	1971-1982	0.959	0.079	0.712	1.142	0.083	-0.997%	-0.997%
	1983-1993	0.851	0.165	0.529	1.311	0.193	-0.555%	-0.776%
	1994-2004	0.757	0.226	0.345	1.306	0.299	-1.137%	-0.896%
	2005-2015	0.648	0.217	0.286	1.304	0.335	-0.935%	-0.906%
	Total	0.807	0.214	0.286	1.311	0.265	-0.906%	
Activity	1971-1982	1.014	0.049	0.837	1.211	0.049	0.118%	0.118%
	1983-1993	1.025	0.088	0.794	1.350	0.086	0.220%	0.169%
	1994-2004	1.062	0.120	0.776	1.475	0.113	0.324%	0.221%
	2005-2015	1.055	0.149	0.773	1.532	0.141	-0.191%	0.118%
	Total	1.038	0.109	0.773	1.532	0.105	0.118%	

The coefficients of variation for intensity, efficiency and activity indices increased more than triple across OECD countries between 1971 and 2015, and the increases were more rapid when moving from 1971-82 to 1983-93. This indicates that some countries may have decreased their energy intensity by improvement in energy efficiency while others may not have been able to achieve this. These variations, thus, buttress the need to further analyse the three indices at the individual country level.

4.2. Country level results of decomposed energy indices

Table 2 shows the decomposition results for the individual country level between 1971 and 2015. The results indicate wide variations in the three indices by country. There are notable disparities in the relative importance of a shift in economic activity and the improvement in energy efficiency across the countries. Between 1971 and 2015, based on the average energy intensity index, 24 of the 30 OECD countries have energy intensities that declined from its respective 1971 levels. For some of the 24 countries, the decline in their energy intensity is due to both improvements in the energy efficiency and shift in economic activity towards less energy intensive activity. That is, energy efficiency and structural shift contributed positively (though at different scale) to the decline in energy intensity. There are 9 countries (Canada, Germany, Iceland, Ireland, Japan, Luxembourg, Netherlands, UK and US) in this category. E.g., the UK's average energy intensity index is 65% of its 1971 level; structural activity and energy efficiency indices are 97% and 67% respectively of their 1971 levels. Consequently, had the composition of economic activity remained constant between 1971 and 2015, energy intensity would have been 67% of its 1971 level. Consequently, 92% of the decline in energy intensity is due to a decline in energy efficiency while the remaining 8% is due to structural shifts.

Table 2: Energy intensity index and decomposition results for OECD country-level

	Indexes values in 2015 (1971=1.00)			Indexes average values (1971-2015)			Indexes average annual change (%) (1971-2015)			Indexes average energy savings in Mtoe (ΔES) (1971-2015)		
	EI	EFF	ACT	EI	EFF	ACT	EI	EFF	ACT	EI	EFF	ACT
Australia	0.68	0.67	1.01	0.91	0.86	1.05	-0.73	-0.75	0.03	11.44	15.26	-3.82
Austria	0.70	0.67	1.04	0.84	0.79	1.06	-0.68	-0.75	0.10	5.63	7.14	-1.51
Belgium	0.58	0.56	1.04	0.75	0.72	1.05	-0.95	-1.00	0.08	15.17	17.63	-2.47
Canada	0.58	0.64	0.92	0.77	0.79	0.97	-0.95	-0.83	-0.19	75.17	65.53	9.64
Chile	0.65	0.62	1.06	0.93	0.90	1.04	-0.79	-0.86	0.13	2.51	3.24	-0.73
Denmark	0.46	0.43	1.07	0.69	0.67	1.04	-1.22	-1.29	0.16	8.54	9.45	-0.90
Finland	0.54	0.49	1.10	0.73	0.70	1.06	-1.04	-1.16	0.23	10.88	12.75	-1.88
France	0.47	0.41	1.14	0.69	0.65	1.08	-1.22	-1.35	0.32	87.75	104.53	-16.78
Germany	0.42	0.42	0.99	0.67	0.69	0.97	-1.32	-1.31	-0.03	157.52	145.94	11.58
Greece	1.36	0.95	1.43	1.28	0.98	1.31	0.81	-0.11	0.97	-3.84	0.38	-4.23
Hungary	0.56	0.53	1.07	0.80	0.77	1.04	-1.00	-1.08	0.15	6.14	7.15	-1.02
Iceland	0.86	0.99	0.87	0.88	0.96	0.91	-0.31	-0.03	-0.28	0.33	0.10	0.23
Ireland	0.27	0.29	0.93	0.63	0.67	0.93	-1.67	-1.62	-0.15	8.39	7.40	0.99
Israel	0.68	0.78	0.87	0.91	1.05	0.87	-0.73	-0.50	-0.30	1.32	-0.18	1.50
Italy	0.65	0.58	1.12	0.77	0.71	1.10	-0.80	-0.96	0.26	43.02	57.50	-14.48
Japan	0.50	0.50	0.99	0.68	0.71	0.97	-1.14	-1.13	-0.02	171.36	159.26	12.10
Korea	0.67	0.47	1.44	0.86	0.72	1.23	-0.74	-1.21	1.01	25.74	54.44	-28.71
Luxembourg	0.27	0.32	0.84	0.56	0.59	0.96	-1.66	-1.54	-0.37	3.80	3.53	0.27
Mexico	0.88	0.64	1.37	1.06	0.87	1.23	-0.27	-0.82	0.85	-4.59	19.07	-23.66
Netherlands	0.55	0.60	0.92	0.84	0.85	0.98	-1.02	-0.91	-0.17	17.17	15.44	1.73
New Zealand	0.99	1.00	0.99	1.18	1.11	1.06	-0.03	0.00	-0.02	-1.54	-0.96	-0.58
Norway	0.59	0.59	1.01	0.78	0.76	1.03	-0.93	-0.94	0.02	7.91	8.79	-0.88
Poland	0.34	0.30	1.14	0.72	0.68	1.10	-1.50	-1.60	0.32	44.16	53.47	-9.31
Portugal	1.18	1.05	1.12	1.21	1.15	1.05	0.40	0.12	0.27	-2.90	-2.12	-0.79
Spain	0.87	0.94	0.93	1.02	1.04	0.98	-0.30	-0.14	-0.16	-1.40	-3.80	2.40
Sweden	0.41	0.39	1.06	0.71	0.69	1.03	-1.34	-1.39	0.14	19.26	20.87	-1.61
Switzerland	0.63	0.65	0.98	0.89	0.88	1.01	-0.83	-0.80	-0.05	3.01	3.13	-0.12
Turkey	1.00	0.84	1.20	1.08	0.98	1.11	0.01	-0.37	0.46	-3.20	2.99	-6.19
UK	0.36	0.40	0.89	0.65	0.67	0.97	-1.46	-1.36	-0.25	106.82	99.29	7.53
US	0.36	0.36	1.01	0.60	0.62	0.98	-1.45	-1.46	0.03	1349.6	1300.6	49.02

For some other countries, the decline in their energy intensity index is predominantly due to a decline in energy efficiency index. The size of the decline in efficiency index dominates the increase in structural shift index such that the net impact decreased the intensity index. 14 countries (Australia, Austria, Belgium, Chile, Denmark, Finland, France, Hungary, Italy, Korea, Norway, Poland, Sweden and Switzerland) are in this set. For Israel only, the decline in its average energy intensity is solely due to structural shifts to less energy-intensive activities while energy efficiency deteriorated.

For the remaining 6 OECD countries, their average energy intensity index increased relative to its 1970 level. Two of these countries (New Zealand and Portugal) have an increased energy intensity index due to deteriorations in their energy efficiency and a structural shift leading to energy dissaving. E.g., the average intensity, efficiency and activity indices for New Zealand were 118%, 111% and 106% respectively of their 1971 levels. Thus, 65% of the increase in energy intensity index was due to shifts toward energy intensive activity while the remaining 35% increase was due to energy inefficiency. Spain achieved favourable shifts in economic activity but failed to improve on its energy efficiency, which eventually led to an increase in its energy intensity index. Finally, Greece, Mexico and Turkey, achieved improvements in their energy efficiency but the dominance of their adverse structural shifts led to an increase in their energy intensity index.

Overall, the decomposition results indicate that many of the OECD countries improved in energy efficiency. Specifically, only 4 of the 30 OECD considered (Israel, New Zealand, Portugal and Spain) became less energy efficient while the remaining 26 countries improved their energy efficiency with a large amount of energy saved. These results are generally consistent with the findings of Oseni (2011) for 16 OECD countries.

As with the aggregate OECD, we use Eq. (4) to measure the total energy (dis)saved (relative to the amount that would have been consumed had energy intensity remained unchanged and the relative amount attributed to improved efficiency and structural change. The last three columns of Table 2 show that 24 OECD countries saved energy – the largest saving of 1349.6 Mtoe is from US. Mexico, followed by Greece, has the largest energy dissaving of 4.6 Mtoe and 3.8 Mtoe respectively.

Further energy decomposition analysis at the individual country was conducted by estimating the average and change in the energy indices, energy savings and share attributed to energy efficiency and structural shift at different time intervals. The results in Table A.3 of the Appendix show significant variation in the indices across time at the country level. For robustness checks, we redo the analysis using LMDI method (stated in footnote 4) and use the spearman rank correlation to compare the results. Correlation coefficients of 0.998 for efficiency index (between FII and LMDI) and 0.977 for structural shift index (between FII and LMDI) shows that the results from LMDI are not different from the abovementioned.

In conclusion, there are considerable variations across time and across countries in the energy efficiency index. Arguably, these variations would have impacted on CO₂ emissions across the countries, yet little is known about the relative extent of the impact. To help examine and quantify the magnitude of the impact, we present the econometric analysis of the impact of changes in energy efficiency on CO₂ emissions controlling for other factors.

4.3. *Empirical results of the determinants of CO₂ emissions*

As discussed in section 2.2, the variables for the econometric analysis include CO₂ emissions per capita, GDP per capita, energy efficiency and structural activity indices (derived from intensity decomposition) and their squared terms to account for a possible non-linear response of CO₂ emissions. We control for cleaner energy substitution and trade openness. All of the variables are in natural log, with the exception of the two control variables, which are in percentages. The summary statistics are in Table A.2 of the Appendix.

We estimate both time series and panel data models as specified in Eqs (8) and (12) respectively. Moreover, since we found Israel, New Zealand, Portugal and Spain to have

become more energy inefficient from the index decomposition analysis, to ensure that the impact of energy efficiency improvements on CO₂ emissions is well estimated in the panel model, we conduct the panel data analysis with (and without) those four countries.

4.3.1. Time series results

The general STSM model combining Eqs (8) - (10) is estimated for each of the 30 OECD countries for the period 1971-2012 (42 observations) saving 2013-2015 (3 observations) for a post-sample prediction test. With the *general-to-specific* principle adopted, the preferred models given in Table 3 were found by testing down from the general model and eliminating statistically insignificant variables but ensuring a range of diagnostics tests are passed.

The results show that, in general, almost all models fit the data well, free of misspecification and instability (as indicated by the results of the predictive failure test) and passing almost all diagnostic tests. The exceptions being Chile, Germany, Korea, UK (where there is a slight problem of heteroscedasticity) and Germany, Korea, Mexico and Spain (where the Box-Ljung test suggests there might be a problem with serial correlation, but the correlation coefficients up to three lags do not suggest there is problem). The reported R^2 s are satisfactorily high, implying strong evidence that the final regressors in the preferred models explain a larger part of the changes in CO₂ emissions. In what follows, we discuss the estimated coefficients with some relevant policy and research implications.

Table 3 shows that the dynamic structures of the preferred model vary across the 30 OECD countries. 26 of the countries displayed immediate adjustment (i.e. no dynamics) despite starting with lags of 2 years, while the lagged dependent variable for the remaining 4 countries is statistically significant in the preferred model. The expected sign of the lagged CO₂ emissions varies and the interpretation is open to discussion. A negative sign may imply that the previous magnitude of CO₂ emissions led to more stringent environmental policy, which makes current CO₂ emissions decline. A positive sign may point to a lack of effective policies (or incentives) in the past to abate CO₂ emissions, leading to a spill over effect that increased current CO₂ emissions. 3 of the 4 countries with a dynamic term indicate a negative effect on CO₂ emissions, while just one country shows positive effect.

Consistent with the results in the existing literature, income generally has a positive significant impact on CO₂ emissions, with some variations in the magnitude – ranging from 0.346 (for Austria) to 1.397 (for Sweden). That is, a 1% increase in income will increase CO₂ emissions by 0.35% and 1.40% for Austria and Sweden respectively. Structural shifts in economic activity likewise have a significant positive impact on CO₂ emissions.²⁷

²⁷ We drop the squared term of the structural shift from the model because it was always found to be insignificant.

Table 3: Preferred STSMs for OECD country-level CO₂ emissions, 1971-2015

Dependent variable: co2 (carbon emission in logs)								
Regressors:	Countries							
	AUS	AUST	BEL	CAN	CHI	DEN	FIN	FRA
$\alpha_0(y)$	0.924*** (0.143)	0.346*** (0.110)	1.357*** (0.126)	0.950*** (0.095)	1.273*** (0.116)	1.380*** (0.228)	0.955*** (0.294)	0.871*** (0.156)
$\beta_0(eff)$	1.145*** (0.112)	0.778*** (0.105)	0.784*** (0.059)	0.703*** (0.086)	1.144*** (0.151)	0.735** (0.273)	0.869*** (0.282)	0.826*** (0.059)
$\gamma_0(eff^2)$	1.813*** (0.342)	-	-	-	-	-1.010** (0.468)	-	-
$\varphi_0(act)$	0.610*** (0.211)	2.077*** (0.255)	1.485*** (0.201)	0.887*** (0.135)	1.376*** (0.424)	1.440** (0.568)	2.895*** (0.924)	0.871*** (0.320)
$\omega_0(TO)$	-0.007** (0.003)	0.002* (0.001)	-0.003*** (0.001)	-	-	-	-0.011*** (0.004)	0.004** (0.002)
$\omega_1(TO_{-1})$	-	-	-	-	0.004** (0.002)	-	-	-
$\psi_0(CES)$	-0.043** (0.016)	-0.016*** (0.004)	-0.008*** (0.001)	-0.012*** (0.002)	-0.032*** (0.004)	-0.080*** (0.028)	-0.023*** (0.004)	-0.011*** (0.001)
$\psi_2(CES_{-2})$	-	-	-	-	0.015*** (0.004)	0.044* (0.032)	-	-
$\lambda_1(co2_{-1})$	-	-	-0.082* (0.041)	-	-	-	-	-
$\partial co2/\partial eff$	0.573	0.778	0.784	0.703	1.144	1.615	0.869	0.826
<i>Long run elasticities</i>								
$\alpha^*(y)$	0.924	0.346	1.254	0.950	1.273	1.380	0.955	0.871
$\beta^*(eff)$	0.573	0.778	0.725	0.703	1.144	1.615	0.869	0.826
$\varphi^*(act)$	0.610	2.077	1.372	0.887	1.376	1.440	2.895	0.871
$\omega^*(TI)$	-0.219	0.139	-0.311	-	0.205	-	-0.615	0.156
$\psi^*(CES)$	-0.071	-0.176	-0.123	-0.236	-0.123	-0.056	-0.417	-0.365
<i>Variance of hyperparameters</i>								
<i>Irregular</i> (10 ⁻⁴)	0.736	1.093	0.000	1.057	1.105	0.129	2.743	0.628
<i>Level</i> (10 ⁻⁴)	0.389	0.578	1.382	0.000	0.000	2.606	0.152	0.000
<i>Slope</i> (10 ⁻⁴)	0.055	-	0.000	0.017	1.563	-	2.331	0.036
<i>Trend:</i>								
<i>Nature of trend</i>	LT	LLT	LLTD	ST	ST	LLT	LT	ST
<i>Interventions</i>	-	Lvl.1990	Lvl.1975	-	-	Irr.1982	-	Irr.2001 Lvl.1989
<i>Diagnostics:</i>								
<i>Equation residuals</i>								
<i>Standard error</i>	0.013	0.014	0.010	0.012	0.021	0.040	0.044	0.010
<i>Normality</i>	0.600	10.527	0.716	15.653	1.732	3.595	1.207	2.281
$h_{(n)}$	1.340 ₍₁₁₎	2.450 ₍₁₁₎	1.337 ₍₁₀₎	1.124 ₍₁₂₎	3.502 ₍₁₀₎	1.233 ₍₁₀₎	1.410 ₍₁₁₎	0.820 ₍₁₁₎
$r_{(1)}$	0.150	-0.030	0.073	-0.025	0.020	-0.101	-0.141	0.023
$r_{(2)}$	-0.067	-0.129	-0.066	-0.260	-0.052	-0.137	-0.227	-0.033
$r_{(3)}$	-0.209	-0.101	-0.042	-0.105	-0.235	0.127	0.203	-0.211
<i>DW</i>	1.602	2.058	1.793	1.973	1.947	2.171	2.126	1.717
$Q_{(p,d)}$	3.754 _(6,4)	2.826 _(5,4)	3.581 _(6,4)	3.924 _(7,5)	4.139 _(6,4)	2.209 _(5,4)	5.705 _(6,4)	3.536 _(6,4)
<i>R-squares</i>	0.804	0.925	0.960	0.867	0.932	0.831	0.781	0.957
<i>Predictive failure tests (2013-2015):</i>								
<i>Failure</i> $\chi^2_{(3)}$	1.698	0.190	3.858	0.206	5.692	5.120	1.271	1.498
<i>Cusum</i> $t_{(3)}$	-1.237	-0.403	-0.034	-0.47	-1.154	0.820	-1.054	-0.454
<i>Likelihood ratio test:</i>								
<i>LR</i> $\chi^2_{(2)}$	25.04***	-	-	-	-	-	29.20***	-
<i>LR</i> $\chi^2_{(1)}$	-	8.42***	25.42***	9.24***	28.32***	11.99***	-	6.13**

Notes of table:

- ***, ** and * indicate 99%, 95% and 90% significance levels respectively; standard errors are in parenthesis; the marginal effect of energy efficiency $\partial co2/\partial eff$ is evaluated at the mean; we derive the long run elasticities using the formula stated in footnote 18; the SR elasticities are the coefficients of the variables at levels and the marginal effect of energy efficiency;
- Nature of trend: the local trend (LT) model is where the trend is stochastic both in the level and slope, i.e., $\sigma_\eta^2 \neq 0$; $\sigma_\xi^2 \neq 0$; local level trend with drift (LLTD) model is where the trend is stochastic in the level but fixed in the slope, i.e. $\sigma_\eta^2 \neq 0$; $\sigma_\xi^2 = 0$; local level trend (LLT) model is where the trend is stochastic in the level but no slope, $\sigma_\eta^2 \neq 0$; and smooth trend (ST) model is where the trend is fixed in the level but stochastic in the slope, i.e. $\sigma_\eta^2 = 0$; $\sigma_\xi^2 \neq 0$.
- Lvl. and Irr. represent level break and irregular intervention dummies respectively, included where necessary for outliers and breaks;
- Normality is the Bowman-Shenton test distributed approximately as $\chi^2_{(2)}$;
- $H_{(n)}$ is the test for heteroscedasticity distributed approximately as $F_{(n,h)}$;
- $r_{(n)}$ are the residual autocorrelation coefficients at lag n distributed approximately as $N(0,1/T)$; *DW* is the Durbin-Watson statistic;
- $Q_{(p,d)}$ is the Box-Ljung Q-statistic based on the first p residuals autocorrelations and distributed approximately as $\chi^2_{(d)}$;
- Failure is the post-sample predictive failure test for 2013-2015 distributed approximately as $\chi^2_{(3)}$;
- Cusum is the test of parameters consistency distributed approximately as the t -distribution;
- LR* test, where applicable, is for the restriction that both σ_η^2 and σ_ξ^2 are equal to zero, distributed as $\chi^2_{(2)}$ or either σ_η^2 or σ_ξ^2 , is equal to zero, distributed as $\chi^2_{(1)}$

Dependent variable: co2 (carbon emission in logs)								
Countries:								
Regressors:	GER	GRE	HUN	ICE	IRE	ISRL	ITA	JAP
$\alpha_0(y)$	0.967*** (0.084)	0.929*** (0.160)	0.883*** (0.059)	0.741*** (0.163)	0.816*** (0.076)	0.670*** (0.167)	1.138*** (0.145)	0.888*** (0.061)
$\beta_0(eff)$	0.934*** (0.062)	0.809*** (0.198)	0.987*** (0.122)	0.576** (0.163)	0.865*** (0.094)	0.633*** (0.133)	0.759*** (0.108)	0.771*** (0.087)
$\gamma_0(eff^2)$	-	-	0.297* (0.157)	-	-	-	-	-0.276** (0.130)
$\varphi_0(act)$	0.948*** (0.208)	1.213*** (0.374)	1.598*** (0.264)	-	0.886*** (0.152)	0.779*** (0.196)	0.640*** (0.225)	1.045*** (0.162)
$\omega_0(TO)$	-	-	-0.001* (0.001)	0.006** (0.003)	0.001* (0.001)	-	0.002* (0.001)	0.005** (0.002)
$\psi_0(ES)$	-0.005* (0.003)	-0.032** (0.013)	-0.006*** (0.002)	-0.012*** (0.003)	-0.029* (0.016)	-0.048* (0.024)	-0.010* (0.005)	-0.008*** (0.001)
$\partial co2/\partial eff$	0.934	0.809	0.821	0.576	0.865	0.633	0.759	0.975
Long run elasticities:								
$\alpha^*(y)$	0.967	0.929	0.883	0.741	0.816	0.670	1.138	0.888
$\beta^*(eff)$	0.934	0.809	0.821	0.576	0.865	0.633	0.759	0.975
$\varphi^*(act)$	0.948	1.213	1.598	-	0.886	0.779	0.640	1.045
$\omega^*(TO)$	-	-	-0.077	0.375	0.105	-	0.076	0.100
$\psi^*(CES)$	-0.049	-0.068	-0.059	-0.853	-0.035	-0.122	-0.054	-0.096
Variance of hyperparameters								
<i>Irregular</i> (10^{-4})	0.557	0.000	1.269	8.658	2.490	0.000	0.000	0.404
<i>Level</i> (10^{-4})	0.000	8.697	0.000	0.000	0.150	9.238	1.417	0.356
<i>Slope</i> (10^{-4})	0.060	0.588	0.057	0.176	0.036	-	0.000	-
Trend:								
<i>Nature of trend</i>	ST	LT	ST	ST	LT	LLT	LLT	LLT
<i>Interventions</i>	-	-	Irr1990 Irr2008	Lvl1988 Lvl1990	-	-	-	Lvl1990
Diagnostics:								
Equation residuals								
<i>Standard error</i>	0.010	0.031	0.014	0.035	0.019	0.028	0.011	0.009
<i>Normality</i>	1.167	0.360	10.660	2.305	0.319	5.040	1.525	2.500
<i>h(n)</i>	2.972** ₍₁₂₎	1.227 ₍₁₂₎	2.821 ₍₁₁₎	1.618 ₍₁₁₎	1.199 ₍₁₁₎	1.659 ₍₁₂₎	1.556 ₍₁₁₎	0.913 ₍₁₁₎
<i>r(1)</i>	0.229	0.017	-0.096	-0.173	0.276	0.017	0.050	-0.009
<i>r(2)</i>	-0.211	-0.091	0.043	-0.044	-0.043	-0.064	-0.055	-0.211
<i>r(3)</i>	-0.117	0.103	-0.216	0.045	-0.221	-0.256	-0.263	-0.035
<i>DW</i>	1.459	1.794	2.054	2.186	1.287	1.396	1.887	1.935
<i>Q(q,p)</i>	14.87*** _(7,5)	2.247 _(7,5)	5.715 _(6,4)	2.411 _(6,4)	5.719 _(6,4)	5.052 _(6,5)	6.163 _(6,4)	2.103 _(5,4)
<i>R-squares</i>	0.903	0.679	0.915	0.826	0.868	0.493	0.917	0.954
Predictive failure tests (2013-2015):								
<i>Failure</i> $\chi^2_{(3)}$	3.949	1.857	0.971	3.337	5.125	0.689	2.168	3.010
<i>Cusum</i> $t_{(3)}$	-0.381	1.261	-0.266	-0.496	0.030	0.677	0.583	-1.392
Likelihood ratio tests:								
<i>LR</i> $\chi^2_{(2)}$	-	19.60***	-	-	3.17*	-	-	-
<i>LR</i> $\chi^2_{(1)}$	23.68***	-	7.85***	16.31***	-	14.52***	23.40***	3.19*

Dependent variable: co2 (carbon emission in logs)							
Regressors:	Countries:						
	KOR	LUX	MEX	NTL	NZD	NOR	POL
$\alpha_0(y)$	0.926*** (0.090)	1.213*** (0.168)	0.928*** (0.081)	0.401** (0.152)	-0.449* (0.226)	0.768*** (0.095)	0.865*** (0.043)
$\beta_0(eff)$	0.573*** (0.099)	0.940*** (0.193)	0.869*** (0.100)	0.468*** (0.081)	0.106 (0.141)	1.942*** (0.342)	0.834*** (0.044)
$\gamma_0(eff^2)$	-	-0.247* (0.132)	-	-	-	1.309*** (0.477)	-
$\varphi_0(act)$	0.948*** (0.221)	1.412*** (0.232)	1.143*** (0.277)	1.120*** (0.322)	0.670** (0.288)	1.456*** (0.228)	0.828*** (0.046)
$\omega_0(TO)$	-	-	-	-	-	0.005** (0.001)	-
$\omega_1(TO_{-1})$	-	-	-	-	0.007* (0.004)	-	-
$\omega_2(TO_{-2})$	-	-	-	-	-	-	-0.002** (0.001)
$\psi_0(CES)$	-0.012*** (0.002)	-0.243** (0.097)	-0.012** (0.001)	-0.043*** (0.015)	-0.019** (0.002)	-0.004** (0.001)	-0.107* (0.053)
$\psi_1(CES_{-1})$	-	-	-	-	-	-0.002* (0.001)	-
$\lambda_1(co2_{-1})$	-	-	-	-	-0.149* (0.082)	-	-
$\partial co2 / \partial eff$	0.573	1.241	0.869	0.468	0.106	1.179	0.834
<i>Long run elasticities:</i>							
$\alpha^*(y)$	0.926	1.213	0.928	0.401	-0.391	0.768	0.865
$\beta^*(eff)$	0.573	1.241	0.869	0.468	0.092	1.179	0.834
$\varphi^*(act)$	0.948	1.412	1.143	1.120	0.583	1.456	0.828
$\omega^*(TO)$	-	-	-	-	0.274	0.319	-0.090
$\psi^*(CES)$	-0.131	-0.071	-0.058	-0.066	-0.449	-0.249	-0.026
<i>Variance of hyperparameters:</i>							
<i>Irregular</i> (10^{-4})	2.668	1.198	0.000	3.054	0.000	4.122	0.051
<i>Level</i> (10^{-4})	0.000	4.847	2.054	0.000	4.122	0.858	0.988
<i>Slope</i> (10^{-4})	2.668	1.829	0.000	0.062	1.093	-	0.018
<i>Trend:</i>							
<i>Nature of trend</i>	ST	LT	LLTD	ST	LT	LLT	LT
<i>Interventions</i>	-	Lvl1973 Lvl2003	-	Lvl.1983	Lvl.1991	-	Lvl.1993
<i>Diagnostics:</i>							
<i>Equation residuals</i>							
<i>Standard error</i>	0.021	0.031	0.013	0.021	0.023	0.023	0.010
<i>Normality</i>	0.075	0.367	2.330	1.444	0.123	6.621	8.674
<i>h(n)</i>	4.254** ₍₁₂₎	2.163 ₍₁₁₎	0.755 ₍₁₁₎	1.610 ₍₁₁₎	0.511 ₍₉₎	0.900 ₍₁₀₎	0.177 ₍₁₀₎
<i>r(1)</i>	0.278	-0.007	0.013	0.238	0.159	-0.136	-0.083
<i>r(2)</i>	-0.423	-0.091	0.219	-0.022	-0.015	0.005	-0.051
<i>r(3)</i>	-0.329	0.165	0.002	-0.177	-0.298	-0.160	-0.170
<i>DW</i>	1.430	1.904	1.863	1.423	1.614	2.227	1.711
<i>Q(q,p)</i>	26.26*** _(6,4)	2.266 _(6,4)	9.617*** _(6,4)	6.153 _(6,4)	4.694 _(6,4)	4.751 _(5,4)	4.144 _(6,4)
<i>R-squares</i>	0.880	0.900	0.887	0.772	0.822	0.849	0.958
<i>Predictive failure tests (2013-2015):</i>							
<i>Failure</i> $\chi^2_{(3)}$	4.178	6.774	1.470	4.254	2.298	1.494	1.311
<i>Cusum</i> $t_{(3)}$	1.146	-0.053	-0.446	-1.470	-0.106	-0.455	0.634
<i>Likelihood ratio tests:</i>							
<i>LR</i> $\chi^2_{(2)}$	-	34.44***	-	-	27.08**	-	22.53***
<i>LR</i> $\chi^2_{(1)}$	35.84***	-	21.12***	7.96**	-	12.18***	-

Dependent variable: co2 (carbon emission in logs)							
Regressors:	Countries:						
	POR	SPA	SWE	SWZ	TUR	UK	US
$\alpha_0(y)$	0.968*** (0.077)	0.784*** (0.160)	1.397*** (0.219)	0.986*** (0.056)	1.126*** (0.056)	1.099*** (0.082)	0.967*** (0.077)
$\beta_0(eff)$	0.924*** (0.125)	0.525*** (0.161)	1.542*** (0.136)	1.475*** (0.070)	0.854*** (0.079)	1.192*** (0.168)	0.479** (0.175)
$\gamma_0(eff^2)$	-	-	-	0.591*** (0.165)	-1.120* (0.555)	0.367** (0.172)	-0.460** (0.134)
$\varphi_0(act)$	0.705*** (0.247)	0.623* (0.366)	1.772*** (0.389)	1.216*** (0.199)	0.844*** (0.128)	-	0.940*** (0.159)
$\omega_0(TO)$	-	0.005** (0.002)	-0.004** (0.002)	-	-	0.003* (0.001)	-
$\omega_1(TO_{-1})$	-	-	-	-	-	-	0.009*** (0.003)
$\psi_0(ES)$	-0.023*** (0.002)	-0.019*** (0.002)	-0.006*** (0.001)	-0.002*** (0.001)	-0.033*** (0.003)	-0.008*** (0.002)	-0.013** (0.005)
$\lambda_1(co2_{-1})$	-	-	0.211*** (0.075)	-	-	-0.042*** (0.052)	-
$\partial co2 / \partial eff$	0.924	0.525	1.542	1.319	0.904	0.872	0.968
<i>Long run elasticities:</i>							
$\alpha^*(y)$	0.968	0.784	1.771	0.986	1.126	1.055	0.967
$\beta^*(eff)$	0.924	0.525	1.954	1.319	0.904	0.837	0.968
$\varphi^*(act)$	0.705	0.623	2.246	1.216	0.844	-	0.940
$\omega^*(TO)$	-	0.179	-0.321	-	-	0.114	0.168
$\psi^*(ES)$	-0.151	-0.271	-0.309	-0.071	-0.154	-0.065	-0.115
<i>Variance of hyperparameters:</i>							
<i>Irregular</i> (10^{-4})	2.624	0.000	4.097	0.554	1.113	0.436	0.185
<i>Level</i> (10^{-4})	2.248	6.128	0.766	0.117	0.000	0.319	0.567
<i>Slope</i> (10^{-4})	-	-	-	-	0.180	0.020	0.000
<i>Trend:</i>							
<i>Nature of trend</i>	LLT	LLT	LLT	LLT	ST	LT	LLTD
<i>Interventions</i>	-	-	-	Lvl.1978	-	Irr.1984, Irr.2001 Lvl.2001	Lvl.1989 Irr.2010
<i>Diagnostics:</i>							
<i>Equation residuals</i>							
<i>Standard error</i>	0.024	0.023	0.023	0.009	0.015	.010	0.008
<i>Normality</i>	1.026	7.811	3.667	1.361	1.268	14.960	1.007
$H_{(h)}$	1.135 ₍₁₂₎	0.412 ₍₁₂₎	1.584 ₍₁₁₎	1.149 ₍₁₁₎	0.401 ₍₁₁₎	4.108 ₍₁₀₎	1.551 ₍₁₀₎
$r_{(1)}$	-0.007	-0.059	-0.173	-0.089	0.028	-0.138	-0.286
$r_{(2)}$	-0.149	0.206	-0.019	0.046	0.039	-0.012	-0.138
$r_{(3)}$	0.178	0.115	-0.013	-0.432	-0.202	0.022	0.283
<i>DW</i>	1.969	1.976	2.306	2.068	1.908	1.755	2.515
$Q_{(q, d)}$	6.270 _(6,5)	10.489 _(6,5)	7.245 _(5,4)	8.152 _(5,4)	6.663 _(6,4)	6.289 _(6,4)	6.849 _(6,4)
<i>R-squares</i>	0.888	0.826	0.861	0.982	0.929	0.948	0.935
<i>Predictive Failure tests (2013-2015):</i>							
<i>Failure</i> $\chi_{(3)}$	1.702	2.367	1.934	5.494	2.896	7.400	0.733
<i>Cusum</i> $t_{(3)}$	0.708	0.320	-0.220	-1.896	1.498	1.619	-0.402
<i>Likelihood ratio tests:</i>							
$LR \chi_{(2)}$	-	-	-	-	-	9.25***	-
$LR \chi_{(1)}$	12.65***	46.71***	12.64***	10.82***	26.01***	-	4.82**

This means for the OECD countries whose economy compositions were found shifting towards less energy-intensive sectors (i.e. declining activity index), their CO₂ emissions decrease and vice versa. The coefficients vary from 0.610 (Australia) to 2.895 (for Finland).

Similarly, the energy efficiency index generally has a significant positive impact on CO₂ emissions. A positive relationship with CO₂ emissions implies that as the energy efficiency index decreases (i.e. energy efficiency improvement) CO₂ emissions decreases. The coefficients vary from 0.468 (Netherlands) to 1.942 (Norway). Also, the squared term of the efficiency index for 10 OECD countries was also found to be significant and 5 of the square-terms (for Denmark, Japan, Luxembourg, Turkey and US) have a negative sign. Since these 5 countries have declining energy efficiency index from the start, the nonlinear effect of energy efficiency on CO₂ emission forms a U-shape, i.e., the declining energy efficiency index decreases CO₂ emissions to a certain minimum after which it starts to increase CO₂ emissions. Thus, there is a declining return to energy efficiency (in terms of marginal reduction in CO₂ emission over time). In contrast, the other 5 countries (Australia, Hungary, Norway, Switzerland and UK) with positive sign indicate an increasing return to their energy efficiency in terms of reduction in CO₂ emission over time. For the remaining 20 countries, the energy efficiency index has precisely a linear positive impact of CO₂ emissions.

Lastly, the control variables (cleaner energy substitution and trade openness) included in the model also have significant impacts on CO₂ emissions. As expected, cleaner energy substitution has a negative impact on CO₂ emissions. Also, for Chile, Denmark and Norway the lagged terms of cleaner energy substitution have significant impacts on CO₂ emissions. Thus, cleaner energy substitution is an important factor that has to be accounted for in a model of this nature. The impacts of trade openness on CO₂ emissions confirm the mixed evidence in the literature on whether trade openness is good for the environment.

With some dynamics in the preferred models, we are able to separate the short run (SR) from the long run (LR) elasticities (also reported in Table 3).²⁸ There are variations in the LR income-, efficiency-, structural shift-, cleaner energy substitution-, and trade openness -elasticities of CO₂ emissions. Structural shift in the composition of the economy has the highest LR elasticities ranging from 0.610 (Australia) to 2.895 (Finland). Next is energy efficiency with LR elasticities varying from 0.092 (Netherlands) to 1.954 (Sweden). Trade openness and cleaner energy substitution have the least absolute LR elasticities ranging from 0.076 (Italy) to 0.615 (Finland), and 0.026 (Poland) to 0.853 (Iceland) respectively.

²⁸ We derive LR elasticities using the formula stated in footnote 18; SR elasticities are the coefficients of the variables at levels and the marginal effect of energy efficiency.

Of interest also is the difference between the SR and LR energy efficiency elasticities. Of the 4 countries that we separated their SR from LR energy efficiency effects (due to the significance of the dynamic terms), 3 have a $SR > LR$ and 1 has a $SR < LR$. Perhaps it is reflecting the time-lag taken for CO₂ emissions to fully respond to improvement in energy efficiency. It may also be linked to possible impacts of (indirect) rebound effects of energy efficiency on CO₂ emissions. Energy efficiency improvement may lead to rebound effects that could potentially results in the total or partial erosion of energy savings, thereby reducing CO₂ emissions with a lesser proportion. As such, for Belgium, New Zealand and UK with a $SR > LR$, the improvement in their energy efficiency, which is very significant in reducing CO₂ emissions in the SR, may have resulted in rebound effects that reduce energy savings in the LR, thereby reducing CO₂ emissions with a lesser proportion. For Sweden with a $SR < LR$ suggests that its energy efficiency gains in the SR may have, through learning, continuous awareness and policy, resulted in more energy savings in the LR, thereby reducing CO₂ emissions with a higher proportion. In all, taking into account the possible (indirect) rebound effects, energy efficiency improvement is still very important for protecting the environment.

Apart from the heterogeneity in the estimated elasticities, it is pertinent to emphasize the various estimated UCETs given in Fig. 2. Notably, the *LR* test for all the preferred models shows that setting the hyperparameters to zero for a deterministic trend is rejected so that the UCETs have different stochastic trend. Four different trend specifications, which are clearly non-linear, are observed across the 30 models, i.e. local, local level, local level with drift and smooth trend where the trends are stochastic both in level and slope $\sigma_\eta^2 \neq 0; \sigma_\xi^2 \neq 0$, stochastic in the level but no slope, i.e. $\sigma_\eta^2 \neq 0$, stochastic in the level but fixed in the slope, i.e. $\sigma_\eta^2 \neq 0; \sigma_\xi^2 = 0$, and fixed in the level but stochastic in the slope, i.e. $\sigma_\eta^2 = 0; \sigma_\xi^2 \neq 0$ respectively.

In general, the estimated UCETs show that after controlling for energy efficiency as well as a structural shift in economic activities, income, cleaner energy substitution and trade openness effects, there are still other important exogenous influences. As discussed above, we associate these with noneconomic effects such as lifestyles and tastes, values, awareness and attitudes towards the environment. The exogenous influences as observed in the UCETs vary from one country to another, reflecting country specific effect. Specifically, the general trends of the estimated UCETs for Australia, Finland, Greece, Israel, Mexico, Netherlands, New Zealand, Portugal, Sweden and Turkey are upward sloping over the estimation period, suggesting increasing ‘carbon emitting’ behaviour and lifestyle.

Fig. 2: Estimated UCETs $\hat{\mu}$ (in logs) for preferred OECD country-level STSMs, 1971-2015

Note: solid lines are the estimated UCETs; dotted lines are trends of the estimated UCETs

Table 4: Contribution to the average per annum change in OECD CO₂ emissions (in logs)

		Average percentage (1971-2013) contributions from:					Fitted	Actual	
		y	eff	act	TO	CES	ExNEF	$\Delta\hat{co2}$	$\Delta co2$
OECD	Australia	1.573	-0.502	0.027	-0.166	0.000	0.388	1.320	1.064
	Austria	0.720	-0.732	0.196	0.221	-0.023	-0.011	0.371	0.391
	Belgium	2.304	-1.034	0.119	-0.710	-0.061	-1.523	-0.905	-0.926
	Canada	1.522	-0.674	-0.198	0.000	-0.064	-0.332	0.253	0.005
	Chile	3.148	-1.087	0.145	0.268	0.000	-0.926	1.548	1.736
	Denmark	2.111	-3.026	0.246	0.000	-0.007	-0.079	-0.755	-1.274
	Finland	2.100	-1.430	0.612	-0.315	-0.173	1.077	1.872	0.111
	France	1.434	-1.690	0.273	0.147	-0.379	-0.626	-0.840	-1.280
	Germany	1.850	-1.856	-0.043	0.000	-0.012	-0.561	-0.622	-0.729
	Greece	1.047	-0.143	1.112	0.000	-0.002	0.308	2.321	2.217
	Hungary	1.705	-1.232	0.251	-0.301	-0.027	-1.110	-0.713	-0.722
	Iceland	1.556	0.027	0.000	0.123	-0.889	-0.871	-0.054	-0.244
	Ireland	2.649	-1.982	-0.178	0.360	-0.002	-0.519	0.327	0.183
	Israel	1.313	-0.196	-0.311	0.000	-0.014	0.868	1.660	1.725
	Italy	1.854	-0.934	0.180	0.057	-0.001	-0.941	0.214	0.313
	Japan	1.874	-1.504	0.022	0.042	0.001	0.054	0.489	0.686
	Korea	5.567	-1.020	0.837	0.000	-0.046	-0.131	5.207	4.800
	Luxembourg	3.227	-2.701	-0.795	0.000	-0.001	-2.084	-2.354	-2.395
	Mexico	1.302	-0.745	0.865	0.000	-0.002	0.584	2.004	1.962
	Netherlands	0.692	-0.501	-0.147	0.000	-0.003	-0.134	-0.094	-0.098
New Zealand	0.268	0.037	-0.120	-0.205	-0.294	0.889	0.576	1.026	
Norway	1.801	-1.491	0.039	0.140	-0.005	-0.034	0.450	0.459	
Poland	2.153	-2.301	0.318	-0.141	0.000	-0.136	-0.107	-0.313	
Portugal	1.939	0.100	0.208	0.000	0.004	0.037	2.288	2.358	
Spain	1.419	0.014	-0.118	0.180	-0.076	-0.086	1.333	1.173	
Sweden	2.949	-4.116	0.414	-0.427	-0.268	-0.036	-1.485	-2.189	
Switzerland	0.922	-1.123	-0.028	0.000	-0.042	-0.179	-0.450	-0.472	
Turkey	2.639	-0.244	0.308	0.000	-0.022	0.839	3.520	3.062	
UK	1.944	-1.693	0.000	0.086	-0.011	-1.393	-1.067	-1.038	
US	1.732	-2.313	0.000	0.080	-0.027	-0.018	-0.546	-0.622	

Note: The contributions are based on Eq. (14); we derive fitted changes in CO₂ emissions ($\Delta\widehat{co2}$) by adding the estimated contributions from the variables; actual change in CO₂ emissions ($\Delta co2$) is from the original data.

For the remaining 20 countries, the general trends are downward sloping over time, showing exogenous ‘carbon mitigating’ behaviour and lifestyle. That is, there are improving behaviours, values and lifestyle to conserve the environment in these countries. This confirms the findings in Broadstock and Hunt (2010) and Chitnis and Hunt (2012), and underscore the need to also consider exogenous noneconomic factors such as tastes and lifestyles in energy and environmental models. This is particularly important as there are growing needs for potentially effective regulations or policies to mitigate CO₂ emissions.

To shed more light on the importance of energy efficiency improvement and the noneconomic factors, we estimate Eq. (14) to derive the relative contributions of the drivers to the annual change in CO₂ emissions. The estimated relative contributions of income, efficiency, structural shift, cleaner energy substitution, trade openness and ExNEF over the period 1971-2013 are summarised in Table 4. For most of the OECD countries considered, income has the largest positive contribution driving up the average per annum change in CO₂ emissions. Improving energy efficiency has the biggest contribution in driving down the changes in CO₂ emissions during this period so that despite the relatively strong positive contribution from income, the growth in CO₂ emissions is slowed down considerably.

Although structural shift contributes to the reduction in growth of CO₂ emissions for some countries, its contribution to increasing CO₂ emissions for others is relatively greater. For 21 OECD countries, ExNEF contributes considerably to the decline in growth of CO₂ emissions relative to trade openness and cleaner energy substitution. This implies that the effect of ExNEF, in particular, on CO₂ emissions should not be ignored. Moreover, the fitted average annual change in CO₂ emissions is positive (i.e. increasing) for 17 OECD countries, while the remaining 13 OECD countries have negative change (i.e. decreasing).

Finally, for a robustness check, we compare the fitted average annual change in CO₂ emissions ($\widehat{\Delta co2}$) to the actual average annual change in CO₂ emissions ($\Delta co2$). The last two columns of Table 4 show that the two estimates are very close in value and identical in sign. Also, the fitted changes are in line with the actual changes over the long periods (the graphs are available upon request from authors) indicating strong evidence that our estimates of relative contributions to annual change in CO₂ emissions are reliable for policy formulation.

4.3.2. Panel data results

To complement the time series results, we estimate the panel data model of the impact of energy efficiency improvements on CO₂ emissions for the OECD countries as a group over the period 1971-2015. We report the static panel regression Eq. (11) estimated by the fixed effects in columns I (panel of all OECD) and II (panel of OECD but excluding energy inefficient countries) of Table 5. The dynamic panel regression Eq. (12) estimated by the LSDVC is reported in columns III (panel of all OECD) and IV (panel of OECD excluding energy inefficient country) of Table 5. We start by discussing the diagnostic tests addressing the econometric issues that may arise in the panel model.

The panel data model Eq. (11) may be prone to some econometric issues including unobserved heterogeneity, endogeneity and cross-section dependence. The Hausman test for correlated fixed effects $\chi^2=16.95$ ($pvalue=0.01$) for panel I and $\chi^2=25.13$ ($pvalue=0.00$) for panel II rejected the null of exogeneity in favour of fixed effects method. We used the Durbin-Wu-Hausman technique to test for endogeneity of energy efficiency, structural shift, and trade openness using their first and second lags as instruments. For panel I, the test failed to reject the null hypothesis of exogeneity for the three variables with $\chi^2=3.73$ ($pvalue=0.05$) and 0.17 ($pvalue=0.69$) and 0.12 ($pvalue=0.73$) respectively. Similarly, for panel II, the test failed to reject the null for exogeneity for the three variables with $\chi^2=1.60$ ($pvalue=0.21$), 0.37 ($pvalue=0.54$), and 0.12 ($pvalue=0.73$) respectively and the overall results using IV also remain unchanged from the FE results, thus, endogeneity is not an issue in this model.

Table 5: Estimated panel data of the drivers of OECD CO₂ emissions, 1971-2015

Dependent variable: co2 (carbon emissions in logs)				
Estimation method:	FE	FE	LSDVC	LSDVC
Independent variables	I	II	III	IV
$\phi_0(\text{Constant})$	-7.803*** (0.264)	-7.572*** (0.282)	-	-
$\alpha_0(y)$	1.034*** (0.028)	1.017*** (0.030)	0.285*** (0.023)	0.266*** (0.025)
$\beta_0(\text{eff})$	0.898*** (0.046)	0.819*** (0.069)	0.228*** (0.032)	0.201*** (0.047)
$\gamma_0(\text{eff}^2)$	-0.273*** (0.033)	-0.326*** (0.049)	-0.071*** (0.026)	-0.080*** (0.037)
$\varphi_0(\text{act})$	1.331*** (0.073)	1.438*** (0.089)	0.302*** (0.049)	0.306*** (0.052)
$\omega_0(TO)$	-0.002*** (0.000)	-0.002*** (0.000)	-0.0004*** (0.0002)	-0.0004*** (0.0002)
$\psi_0(\text{CES})$	-0.011*** (0.001)	-0.011*** (0.001)	-0.004*** (0.001)	-0.003*** (0.001)
$\lambda_1(\text{co2}_{-1})$	-	-	0.729*** (0.018)	0.744*** (0.020)
Marginal effect: $\partial \text{co2} / \partial \text{eff}$	1.037*** (0.035)	1.018*** (0.047)	0.265*** (0.026)	0.251*** (0.033)
Time dummies included	Yes	Yes	Yes	Yes
Observations	1350	1170	1320	1144
No. of countries	30	26	30	26
Diagnostics:				
R^2	0.892	0.883	-	-
F -test	4914.50***	7444.57***	-	-
Hausman (χ^2)	16.95**	25.13***	-	-
Restriction test $I: \theta_t = 0$	158.98***	728.32***	85.57***	81.72***
Elasticities	SR (III)	SR (IV)	LR (III)	LR (IV)
$\alpha^*(y)$	0.285***	0.266***	1.054***	1.038***
$\beta^*(\text{eff})$	0.265***	0.251***	0.981***	0.978***
$\varphi^*(\text{act})$	0.303***	0.306***	1.117***	1.196***
$\omega^*(TO)$	-0.026***	-0.025**	-0.098***	-0.099**
$\psi^*(\text{CES})$	-0.053***	-0.051***	-0.196***	-0.198***
Relative contributions	SR (III)	SR (IV)	LR (III)	LR (IV)
Y	0.494%	0.460%	1.826%	1.795%
Eff	-0.469%	-0.454%	-1.731%	-1.772%
Act	0.015%	0.018%	0.057%	0.069%
TO	-0.022%	-0.021%	-0.083%	-0.083%
CES	-0.013%	-0.012%	-0.048%	-0.048%
ExNEF	-0.085%	-0.090%	-0.315%	-0.353%
$\Delta \widehat{\text{co2}}$	-0.080%	-0.100%	-0.295%	-0.392%
Δco2	-0.190%	-0.223%	-0.190%	-0.223%

Notes of the table:

1. All estimations are undertaken in STATA; ***, ** and * denote 99%, 95% and 90% significance levels respectively;
2. Driscoll-Kraay standard errors and bootstrapped standard errors are in parenthesis for FE and LSDVC respectively;
3. All variables in small letters are in log form and variables in capital letters are in levels;
4. Models I & III correspond to Eqs (11) & (12) respectively and both models are estimated using panel data of 30 OECD countries.
5. Models II & IV also correspond to Eqs (11) & (12) respectively but the data exclude the 4 OECD countries (Israel, New Zealand, Portugal and Spain) that we found to be energy inefficient;
6. F -test is test for the joint significant of the parameters;
7. Hausman χ^2 is a specification test for correlated fixed effects;
8. Restriction test I is the F -statistic from the F -test of no fixed time effects restriction;
9. The long run (LR) elasticities for models III and IV are estimated as $\hat{f}_i / (1 - \hat{\lambda}_1)$ where $\hat{f}_i$ and $\hat{\lambda}_1$ are the estimated parameter for variable i and the lagged CO₂ emissions respectively;
10. The relative contributions of the variables to changes in CO₂ emission is based on the panel data version of Eq. (14).

However, FE results may be biased in the presence of cross-sectional correlation. Although OECD is made up sovereign countries with each country having a great deal of autonomy, it is still likely that the countries respond similarly to common shocks implying that their economic performance, energy consumption and hence energy efficiency and CO₂ emissions may be correlated (Moshiri and Duah, 2016). We conduct a test for cross-sectional correlation using Pesaran (2004) test, which follows a standard normal distribution and handles balanced panel as in this case. The Pesaran test values -3.00 (*pvalue*=0.00) and -3.46 (*pvalue*=0.00) for panels I and II respectively reject the null of cross-sectional independency. Consequently, for the FE, we report the Driscoll and Kraay (1998) standard error, which is robust to very general forms of cross sectional and temporal dependence. Finally, the estimates of the standard *F*-test reported in Table 5 clearly reject the null hypothesis that the time dummies are jointly equal to zero for panels I and II implying that time dummies are a significant proxy for UCETs in these panels.

Table 5 shows that the estimated coefficients of the variables are significant and have the expected signs for panel I. Energy efficiency has a nonlinear effect on CO₂ emissions and the marginal effect is computed at the mean value. The degrees of the impact of structural shift and energy efficiency indices on CO₂ emissions are 1.331 and 1.037 respectively. That is, a 1% decrease in efficiency index will reduce CO₂ emissions by 1.037%. Trade openness has the least effect and shows that trade is good for the environment, which slightly deviates from the mixed evidence from the time series model, and the effect is statistically significant. Also, the entire coefficient estimates of the dynamic panel model (panel III) including the lagged dependent variable are significant with the expected signs.

Using 26 OECD countries, which exclude the 4 countries that we found to be energy inefficient, to estimate the static model (panel II) and dynamic model (panel IV) leads to changes in the estimated parameters. The exceptions being the coefficients of trade openness and cleaner energy substitute that are unchanged. Also, the lagged CO₂ emissions for both panels III and IV shows a positive impact on the current level of CO₂ emissions indicating that, if the existing environmental policies have not been effective to abate CO₂ emissions in the previous year, it will lead to a spillover effect that will increase current CO₂ emissions.

There are variations in the elasticities obtained from the dynamic model via LSDVC (reported in Table 5). Specifically, the LR elasticities are about four times the corresponding SR elasticities for panel III, indicating that the variables are more effective in influencing CO₂ emissions in the LR than they do in the SR. With more time, energy efficiency improvements become more significant in mitigating CO₂ emissions.

A 1% increase in energy efficiency will reduce CO₂ emissions by 0.265% in the SR and with a larger size of 0.981% in the LR. This could also be seen as (an indirect) super conservation of rebound effects on CO₂ emissions, in which, energy efficiency gains in the SR result in more energy savings in the LR, thereby reducing CO₂ emissions with a higher proportion. Excluding the 4 energy inefficient countries from the group (i.e. panel IV) leads to just slight changes in the elasticities both in the SR and LR. Thus, the inclusion of the energy inefficient countries in the panel OECD countries has a minimal impact in driving down the net effect of energy efficiency on CO₂ emissions. Notably, the estimated LR elasticities are comparable with the LR elasticities from the time series model. E.g. all the estimated LR elasticities – income (1.054), efficiency (0.981), structural shift (1.117), trade (-0.098) and cleaner energy substitution (-0.196) elasticities for Panel III fall in the range of [-0.391]-[1.771], [0.092]-[1.954], [0.583]-[2.895], [-0.615]-[0.375] and [-0.853]-[-0.026] for the corresponding LR elasticities from the time series model in Table 3.

The trends of the panel data version of the UCETs given by the estimated coefficients of the time dummies are plotted in Fig. 3. Following Adeyemi and Hunt (2007) and Griffin and Schulman (2005), if there have been significant progressions in the ExNEF (such as positive lifestyle, taste, behaviour and attitude towards the environment) that are driving the UCET, we expect the UCET, estimated as $(\hat{\theta}_t/1 - \hat{\lambda}_1)$, to be reflected in declining values. In Fig. 3, the UCETs reflect variation from year to year, which is consistent with the estimated UCETs from the time series model. The large declines in 1974-75 and 1979-80 observed in the UCETs correspond to the period of the OPEC oil embargo and Iran-Iraq war respectively.

These two events arguably led to increases in the price of crude oil and consequently, energy saving and carbon mitigating behaviour. There is also a remarkable decline in 2006-10, the first commitment period of the Kyoto protocol.

The implicit trend of the long run UCET for the 30 countries as a group (panel III) is generally downward slopping – suggesting an exogenous ‘carbon mitigating’ behaviour, attitude, lifestyle etc. Also, excluding the 4 energy inefficient countries makes the long run UCET (panel IV) shift further downward. The observed trends of the UCET for the group of the countries are not surprising given that 20 of the 30 countries show downward sloping trend in their individual UCET in the time series model given in Fig. 2.

Lastly, using the panel data version of Eq. (14), we quantify the contributions of the drivers to the annual change in CO₂ emissions. This is shown in Fig. 4 and summarised at the end of Table 5. The results further highlight the importance of the improvement in energy efficiency and ExNEF (captured by UCET) to the environment. It is clear from Fig. 4 that the relative contributions of the variables driving the annual change in CO₂ emissions are relatively stable over the period. Income and structural shift towards energy-intensive industries remain significant positive drivers for most of the period. Increasing income makes the largest positive contribution, on average 1.826% per annum followed by structural shift with about 0.057% per annum as in the end of Table 5 (panel III (LR (III))).

In contrast, improved energy efficiency, trade openness, cleaner energy substitution and ExNEF are driving down the growth in CO₂ emissions. Among these drivers, energy efficiency improvement constitutes the largest share, on average 1.731% per annum. Thus, despite the relatively strong positive contributions from income and structural shift, the annual growth in CO₂ emissions slowed down significantly, driven primarily by energy efficiency and the relatively small contributions from ExNEF, trade openness and cleaner energy substitution. These results are broadly consistent with the time series results reported in Table 3.

5. Concluding remarks

This paper develops a two-step method to examine the effect of energy efficiency improvement on CO₂ emissions at the macro level for 30 OECD countries. First, an index decomposition analysis is used to derive energy efficiency from energy intensity. Secondly, we use STSM and LSDVC models in a modified dynamic 3E framework to examine and quantify the impact of energy efficiency improvement on CO₂ emissions controlling for other factors including the exogenous noneconomic factors (ExNEF) such as taste, lifestyle etc.

Our findings of the first step, the decomposition results for the OECD as a group, indicate that most of the decreases (i.e. progressions) in energy intensity between 1971 and 2015 occur due to improvements in energy efficiency while structural shift was found to be driving up energy intensity in recent time. At the country level, the decomposition results shows that the average (1971-2015) share of improvements in energy efficiency in the overall decline in energy intensity ranges from 32.1% (for Iceland) to 94.5% (for US) and more than 100% for Australia, Austria, Belgium, Chile, Denmark, Finland, France, Hungary, Italy, Korea, Norway, Poland, Sweden and Switzerland (as the share of structural shift index in the decline in energy intensity in these countries are negative). Only 4 countries, Israel, New Zealand, Portugal and Spain, were found to be having deteriorating energy efficiency indices. These results are generally similar to the findings of Oseni (2011) for 16 OECD countries.

In the second step, the econometric analysis highlights some important results. For OECD as a group, improvements in energy efficiency reduce CO₂ emissions and with a higher reduction in the long run. Energy efficiency improvement presents the biggest contribution to driving down CO₂ emissions, on average 1.731% per annum, so that despite the relatively strong positive contribution from income, the growth in CO₂ emissions slows down considerably. The impacts of trade openness on the environment are mixed for the individual countries but they are found to be good for the environment at the group level.

Cleaner energy substitution (i.e., renewable and nuclear energy share) contributes to driving down CO₂ emissions but is not as important as energy efficiency improvement.

More importantly, the UCET, which captures the non-economic factors is downward slopping for the OECD countries as a group, indicating ‘carbon mitigating’ lifestyle, taste or/and attitude to the environment. This stems from the fact that 20 of the 30 countries we considered, showed downward trends in their various stochastic UECTs obtained from the time series model. The quantification of the contribution of the non-economic factors to the decrease in CO₂ emissions using the estimated UCET shows a significant share, on average 0.315% per annum. In all, the time series results and the panel data results are generally comparable and excluding the 4 countries that are found to becoming more energy inefficient from the panel of OECD countries slightly improves the panel data results.

Several important policy implications emerged from this study. Improving energy efficiency remains a key option for mitigating CO₂ emissions and conserving energy for future use. Although we found cleaner energy substitution not to be as effective as energy efficiency to mitigate CO₂ emissions for our data set, in a balanced policy package, policy makers could combine improving energy efficiency with cleaner energy substitutes. Similarly, action on factors such, attitudes, lifestyles, behaviours, etc. are essential to protect the environment given the non-trivial contribution of these exogenous non-economic factors to changes in CO₂ emissions. Effective policy action would entail stimulating behavioural and other non-economic changes for a positive environmental conservation, especially for countries that exhibit carbon-emitting attitudes, lifestyles, behaviours, etc. which are harmful to the environment.

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Appendix

Table A.1: Descriptive statistics of variables for energy intensity decomposition

<i>I.</i>	<i>Economic activity</i>		<i>Measure:</i> <i>Constant 2005 prices, billion US\$</i>				<i>Measure:</i> <i>% share of total GDP</i>			
			Mean	SD	Min.	Max.	Mean	SD	Min.	Max.
Mining	Value added	Y_1	40.74	84.51	0.10	645.40	5.20	4.74	0.91	29.28
Manufacturing	Value added	Y_2	140.66	269.78	0.66	1846.26	14.87	3.77	4.34	29.65
Construction	Value added	Y_3	57.64	106.72	0.63	654.10	6.53	2.14	2.99	16.10
Transport	Value added	Y_4	76.45	173.19	0.30	1573.16	7.82	1.94	3.00	14.56
Agriculture	Value added	Y_5	15.72	21.34	0.09	148.11	3.08	2.95	0.20	25.17
Commercial	Value added	Y_6	557.69	1282.87	2.07	9908.33	54.17	7.16	34.64	77.25
Residential	HCE	Y_7	553.56	1232.03	2.97	10343.50	56.47	7.35	34.03	86.02
Total	GDP	Y	922.52	1893.75	4.90	15083.40	100.0	0.00	100.0	100.0
<i>II.</i>	<i>Energy consumption</i>		<i>Measure:</i> <i>Million tonne of oil equivalent</i>				<i>Measure:</i> <i>% share of total energy use</i>			
			Mean	SD	Min.	Max.	Mean	SD	Min.	Max.
Mining	Energy use	E_1	14.56	34.40	0.03	224.22	11.49	4.51	1.57	28.52
Manufacturing	Energy use	E_2	33.58	69.51	0.20	449.06	30.47	8.30	12.37	68.88
Construction	Energy use	E_3	0.55	1.42	0.00	16.70	0.65	0.61	0.00	3.97
Transport	Energy use	E_4	32.58	93.02	0.10	633.71	23.71	7.68	7.02	58.25
Agriculture	Energy use	E_5	2.02	3.27	0.00	25.61	2.99	2.82	0.00	20.00
Commercial	Energy use	E_6	13.67	34.45	0.03	228.59	9.88	5.00	0.81	42.21
Residential	Energy use	E_7	20.96	43.71	0.15	277.66	20.82	7.42	4.18	52.75
Total	Energy use	E	117.92	275.68	0.87	1729.98	100.0	0.00	100.0	100.0

Note: ¹ Data are for 30 OECD countries covering the period of 1971-2015; HCE is household consumption expenditure and GDP is Gross Domestic Product; Mtoe is million tonnes of oil equivalent

² Economic activities data are sourced from the United Nation Statistics Division (UNSD) via <http://data.un.org/>; energy use data are sourced from the International Energy Agency (IEA), Energy balance of the OECD countries via <http://stats.ukdataservice.ac.uk>

Table A.2: Descriptive statistics for the drivers of changes in CO₂ emissions, 1971-2015

<i>Variable:</i> <i>Statistics:</i>	<i>CO₂:</i> co2 emissions (tonne per capita)		<i>Y:</i> income (GDP constant 2005 prices, US\$ per capita)		<i>EFF:</i> energy efficiency index (1971=1)		<i>ACT:</i> structural shift index (1971=1)		<i>TO:</i> trade openness (import + export % of GDP)		<i>CES:</i> cleaner energy substitution (alternative & energy % of total energy use)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Australia	15.317	2.124	29859.760	7237.357	0.863	0.122	1.055	0.023	31.355	10.726	1.653	0.299
Austria	7.438	0.719	30664.320	7607.216	0.793	0.097	1.055	0.022	69.470	21.916	10.991	1.520
Belgium	10.825	1.450	29596.740	6689.389	0.717	0.132	1.054	0.020	112.263	31.866	16.651	7.791
Canada	15.949	0.736	29442.830	5841.763	0.793	0.114	0.966	0.031	52.618	14.695	19.673	3.590
Chile	2.701	0.961	5487.411	2374.319	0.897	0.118	1.036	0.021	51.212	18.005	7.243	1.524
Denmark	10.259	1.718	39272.240	8280.936	0.668	0.177	1.041	0.040	67.663	23.181	1.559	2.101
Finland	10.520	1.263	29350.310	8056.110	0.700	0.163	1.057	0.050	55.887	18.448	18.144	6.498
France	6.366	1.240	28684.550	5756.529	0.647	0.170	1.078	0.047	39.075	13.422	33.166	16.187
Germany	11.247	1.577	29500.330	6711.361	0.689	0.189	0.967	0.022	48.942	21.714	9.826	4.399
Greece	6.317	1.707	17304.310	3297.284	0.985	0.068	1.309	0.149	36.264	15.674	2.121	1.193
Hungary	6.032	1.135	8711.735	1963.642	0.774	0.163	1.041	0.031	77.460	62.185	9.908	6.937
Iceland	7.378	0.838	43069.840	10901.750	0.959	0.080	0.913	0.063	62.479	5.590	71.060	12.158
Ireland	8.490	1.319	30694.270	15136.680	0.672	0.201	0.933	0.029	104.887	51.608	1.210	1.027
Israel	7.021	1.654	17248.220	4331.599	1.048	0.126	0.871	0.047	65.860	11.385	2.538	1.840
Italy	6.550	0.710	25857.510	5315.414	0.705	0.120	1.096	0.042	38.065	11.395	5.365	1.185
Japan	8.324	0.806	29962.100	7601.257	0.706	0.152	0.969	0.034	20.032	6.067	12.008	5.732
Korea	6.568	3.334	11531.990	7507.749	0.717	0.159	1.225	0.129	49.202	24.740	10.950	6.391
Luxembourg	26.131	8.561	55304.790	21317.650	0.587	0.241	0.960	0.078	247.543	59.819	0.294	0.149
Mexico	3.168	0.587	6982.628	1032.792	0.874	0.122	1.229	0.112	33.162	19.907	4.868	1.531
Netherlands	10.035	0.525	33275.710	7939.237	0.849	0.163	0.980	0.026	93.360	31.431	1.526	0.435
New Zealand	6.516	0.949	23099.650	4084.766	1.111	0.098	1.055	0.048	45.002	11.911	27.150	3.377
Norway	6.882	0.664	50328.140	14312.160	0.758	0.128	1.034	0.031	63.808	7.545	41.583	4.320
Poland	9.189	1.491	6507.554	2289.039	0.677	0.275	1.097	0.116	44.893	26.406	0.243	0.227
Portugal	3.782	1.382	14534.750	3914.853	1.149	0.116	1.050	0.044	47.384	18.306	6.586	2.584
Spain	5.433	1.084	20071.410	5019.718	1.041	0.070	0.985	0.051	35.768	16.360	14.251	4.785
Sweden	6.736	1.910	34238.260	7781.721	0.689	0.193	1.032	0.034	63.236	19.870	40.616	11.855
Switzerland	5.824	0.445	48940.030	6609.728	0.883	0.106	1.007	0.016	80.040	23.149	35.665	6.456
Turkey	2.527	0.869	5525.797	1699.889	0.981	0.081	1.110	0.055	28.850	14.767	4.681	1.887
UK	9.157	1.234	31625.620	8071.191	0.671	0.182	0.967	0.032	39.702	11.034	8.402	2.688
US	19.166	1.556	34659.460	8206.039	0.616	0.193	0.978	0.022	18.698	6.944	8.839	3.003
Panel I	8.728	5.316	26711.080	15406.810	0.807	0.214	1.038	0.109	60.806	48.315	14.292	16.790
Panel II	9.196	5.521	27937.620	16068.630	0.764	0.192	1.046	0.110	62.699	51.143	14.548	17.596

Notes of table: ¹ Data are for 30 OECD countries covering the period of 1971-2015; Panel I is for the 30 OECD as a group and Panel II excludes Israel New Zealand, Portugal and Spain

² CO₂ emissions per capita is sourced from IEA database via <http://stats.ukdataservice.ac.uk>; trade openness is proxy by trade (import plus export) as a % share of GDP. Both total export, import and GDP data for estimating trade openness are sourced from UN statistical division database via <http://data.un.org/>; cleaner energy substitute is proxy by alternative and nuclear energy as a % share of total energy use and sourced alongside the population data used to derive income per capita (Y) from the World Bank database -world development indicators via <http://databank.worldbank.org>; EFF and ACT are energy efficiency index and structural shifts index respectively derived from energy intensity decomposition

Table A.3: Energy indices and energy (dis)saving at different time intervals for OECD country-level

Country	Indices	Average indices (1971=1)				Changes in indices (%)				Energy savings (Mtoe)				Contribution to savings (%)			
		1971	1983	1994	2005	1971	1983	1994	2005	1971	1983	1994	2005	1971	1983	1994	2005
		1971	1983	1994	2005	1971	1983	1994	2005	1971	1983	1994	2005	1971	1983	1994	2005
		82	93	04	15	82	93	04	15	2	3	4	5	82	93	4	15
Australia	EI	1.07	0.95	0.86	0.73	0.7	1.2	1.1	1.1	3.5	2.57	12.8	33.8	1.0	1.0	1.0	1.0
		2	9	1	3	00	93	62	76	00	4	07	76	00	00	00	00
	EF	1.02	0.90	0.80	0.71	0.2	1.4	0.9	0.8	1.1	6.46	18.5	37.2	0.4	3.4	1.5	1.1
		3	0	3	0	17	11	71	44	40	2	13	10	60	99	51	12
Austria	AC	1.04	0.06	0.07	0.03	0.4	0.2	0.1	0.4	2.3	3.88	5.70	3.33	0.5	2.4	0.5	0.1
		8	6	2	3	72	20	54	23	60	8	6	4	40	99	51	12
	EI	0.95	0.85	0.78	0.73	1.0	0.5	0.1	0.8	0.9	3.61	7.09	10.8	1.0	1.0	1.0	1.0
		5	7	5	2	82	98	71	83	90	4	1	28	00	00	00	00
Belgium	EF	0.92	0.81	0.72	0.69	1.3	0.6	0.4	0.4	1.7	4.81	9.33	12.6	1.6	1.3	1.3	1.1
		3	4	8	3	93	82	47	77	37	6	1	89	56	44	16	83
	AC	1.03	0.05	0.07	0.05	0.3	0.1	0.4	0.5	0.7	1.20	2.24	1.86	0.6	0.3	0.3	0.1
		6	3	9	6	68	45	17	33	47	3	0	0	56	44	16	83
Canada	EI	0.93	0.73	0.72	0.60	2.0	0.4	0.3	0.8	2.7	12.4	16.5	28.9	1.0	1.0	1.0	1.0
		7	4	5	5	86	79	73	81	40	68	46	18	00	00	00	00
	EF	0.90	0.68	0.67	0.58	2.4	0.4	0.3	0.7	4.1	15.1	19.9	31.2	1.5	1.2	1.2	1.0
		5	8	8	0	43	81	64	10	73	09	94	59	18	16	12	83
Chile	AC	1.03	0.06	0.07	0.04	0.4	0.0	0.0	0.2	1.4	2.64	3.44	2.34	0.5	0.2	0.2	0.0
		7	8	0	2	89	41	19	29	33	2	8	1	18	16	12	83
	EI	0.94	0.77	0.70	0.62	1.4	0.6	1.0	0.6	11.	51.0	89.6	148.	1.0	1.0	1.0	1.0
		5	6	9	3	64	15	31	75	013	85	95	897	00	00	00	00
Denmark	EF	0.95	0.80	0.72	0.67	0.8	0.9	1.0	0.4	8.5	43.4	85.0	125.	0.7	0.8	0.9	0.8
		5	6	2	2	94	92	16	09	46	55	19	117	01	46	49	42
	AC	0.98	0.96	0.98	0.92	0.6	0.3	0.0	0.4	2.4	7.63	4.67	23.7	1.7	0.1	0.0	0.1
		8	2	2	7	32	88	62	41	67	0	6	81	01	54	51	58
Finland	EI	1.02	0.99	0.93	0.75	0.2	0.3	0.2	2.2	0.1	0.10	1.44	8.60	1.0	1.0	1.0	1.0
		1	6	4	6	61	72	95	13	16	4	4	9	00	00	00	00
	EF	1.00	0.97	0.88	0.72	0.5	0.1	0.7	1.9	0.0	0.38	2.66	9.85	0.8	0.2	2.2	1.1
		2	0	3	6	82	68	32	72	40	4	9	5	41	83	52	60
France	AC	1.01	0.02	0.05	0.04	0.3	0.2	0.5	0.1	0.1	0.28	1.22	1.24	0.1	0.7	1.2	0.1
		9	7	8	2	43	16	34	56	56	0	4	6	59	17	52	60
	EI	0.90	0.71	0.60	0.51	2.6	0.1	1.2	0.9	1.7	6.22	10.8	15.3	1.0	1.0	1.0	1.0
		9	1	6	5	46	25	02	06	23	2	65	70	00	00	00	00
Germany	EF	0.91	0.69	0.56	0.48	2.4	0.5	1.3	0.7	1.6	6.62	12.5	16.9	0.9	1.0	1.1	1.1
		4	7	0	1	95	65	84	11	33	6	91	37	28	56	60	03
	AC	0.99	0.02	0.08	0.07	0.2	0.6	0.4	0.2	0.0	0.40	1.72	1.56	0.0	0.0	0.1	0.1
		5	2	3	0	09	44	86	82	90	4	6	7	72	56	60	03
Italy	EI	0.91	0.75	0.68	0.56	1.8	0.0	1.5	0.7	2.0	7.37	12.4	21.5	1.0	1.0	1.0	1.0
		8	2	3	0	78	08	91	01	59	5	90	84	00	00	00	00
	EF	0.91	0.73	0.62	0.50	1.8	0.4	1.7	0.5	2.0	7.92	15.6	25.3	0.9	1.0	1.2	1.1
		7	6	0	6	88	27	57	57	85	0	37	73	47	78	62	76
Japan	AC	1.00	0.02	0.10	0.10	0.0	0.5	0.5	0.1	0.0	0.54	3.14	3.79	0.0	0.0	0.2	0.1
		1	1	3	7	12	63	02	59	25	5	7	0	53	78	62	76
	EI	0.89	0.70	0.62	0.51	2.3	0.5	0.7	1.1	20.	65.2	104.	161.	1.0	1.0	1.0	1.0
		7	5	9	4	73	61	95	34	179	97	135	386	00	00	00	00
United Kingdom	EF	0.87	0.67	0.56	0.45	2.6	0.6	1.0	1.0	24.	74.8	127.	191.	1.2	1.1	1.2	1.1
		7	0	8	3	16	96	79	00	433	88	250	539	38	45	18	88
	AC	1.02	0.05	0.10	0.13	0.3	0.2	0.6	0.0	4.2	9.59	23.1	30.1	0.2	0.1	0.2	0.1
		4	3	8	3	41	54	85	17	55	1	15	54	38	45	18	88

Germany	EI	0.92	0.72	0.54	0.45	-	-	-	-	24.347	105.327	209.579	290.822	1.000	1.000	1.000	1.000
		6	2	8	3	1.761	1.855	0.809	0.859								
		0.93	0.75	0.58	0.46	-	-	-	-	21.627	92.242	188.584	281.295	0.958	0.867	0.897	0.966
		4	2	3	6	1.479	1.742	1.056	0.962								
Greece	AC	0.99	0.95	0.94	0.97	-	-	-	-	2.720	13.085	20.995	9.527	0.042	0.133	0.103	0.034
		1	9	1	4	0.336	0.273	0.333	0.173								
		0.08	0.32	0.43	0.31	-	-	-	-	0.884	3.557	5.924	5.005	1.000	1.000	1.000	1.000
		5	7	3	2	1.373	2.495	0.900	0.292								
Hungary	EI	0.99	0.92	0.92	0.89	-	-	-	-	0.138	0.320	0.290	2.010	0.038	0.042	0.049	0.408
		0	4	5	9	0.450	0.958	1.422	0.484								
		0.09	0.29	0.40	0.46	-	-	-	-	1.022	3.237	5.634	7.015	1.038	0.958	0.951	1.408
		8	5	0	0	1.918	1.264	1.133	0.444								
Iceland	EI	0.96	0.88	0.74	0.59	-	-	-	-	0.877	2.795	6.919	13.954	1.000	1.000	1.000	1.000
		3	9	7	3	0.780	0.531	1.923	0.768								
		0.95	0.86	0.70	0.55	-	-	-	-	1.098	3.457	8.339	15.714	1.169	1.255	1.205	1.128
		6	5	4	5	1.083	0.448	2.154	0.632								
Ireland	AC	0.00	0.02	0.06	0.06	-	-	-	-	0.221	0.662	1.420	1.760	0.169	0.255	0.205	0.128
		9	8	3	8	0.344	0.080	0.493	0.159								
		0.99	0.89	0.78	0.80	-	-	-	-	0.006	0.190	0.489	0.616	1.000	1.000	1.000	1.000
		9	6	7	9	0.343	1.187	0.886	1.172								
Israel	EI	0.01	0.95	0.88	0.97	-	-	-	-	0.020	0.090	0.259	0.059	0.387	2.561	0.531	0.007
		7	2	1	9	0.056	0.853	0.511	1.189								
		0.98	0.94	0.89	0.82	-	-	-	-	0.026	0.099	0.230	0.557	0.613	1.561	0.469	1.007
		2	1	4	7	0.396	0.407	0.490	0.155								
Italy	EI	0.87	0.72	0.52	0.37	-	-	-	-	1.003	2.792	10.039	19.729	1.000	1.000	1.000	1.000
		2	8	1	8	2.015	1.093	2.084	1.476								
		0.90	0.78	0.56	0.41	-	-	-	-	0.717	2.203	8.857	17.837	0.745	0.769	0.882	0.901
		6	1	2	6	1.283	1.416	1.955	1.838								
Japan	AC	0.96	0.93	0.92	0.91	-	-	-	-	0.286	0.589	1.181	1.892	0.255	0.231	0.118	0.099
		1	3	6	0	0.853	0.270	0.521	0.486								
		0.91	0.97	0.96	0.79	-	-	-	-	0.449	0.195	0.532	4.116	1.000	1.000	1.000	1.000
		6	0	0	1	0.988	0.970	0.549	2.371								
Korea	EI	1.00	0.13	0.15	0.89	-	-	-	-	0.050	0.945	1.736	2.014	0.099	5.614	11.955	0.430
		9	1	9	5	0.156	2.138	1.380	2.932								
		0.90	0.86	0.83	0.88	-	-	-	-	0.499	1.140	2.267	2.102	1.099	6.614	12.955	0.570
		9	0	0	3	1.125	0.721	0.500	0.163								
Netherlands	EI	0.91	0.74	0.71	0.68	-	-	-	-	11.822	40.127	55.614	64.511	1.000	1.000	1.000	1.000
		6	7	2	6	1.999	0.400	0.125	0.694								
		0.87	0.69	0.62	0.60	-	-	-	-	17.326	50.676	76.614	85.394	0.893	1.258	1.377	1.327
		8	3	7	7	2.389	0.564	0.370	0.506								
Portugal	AC	1.04	0.07	0.13	0.12	-	-	-	-	5.504	10.549	21.000	20.883	0.107	0.258	0.377	0.327
		5	9	7	9	0.529	0.292	0.439	0.202								

Country	Indices	Average indices (1971=1)				Changes in indices (%)				Energy savings (Mtoe)				Contribution to savings (%)			
		1971	1983	1994	2005	1971	1983	1994	2005	1971	1983	1994	2005	1971	1983	1994	2005
Japan	EI	0.90	0.64	0.61	0.54	-	-	-	-	33.983	158.186	214.765	278.500	1.000	1.000	1.000	1.000
		0	9	7	6	2.549	0.935	0.212	0.873								
		0.92	0.69	0.65	0.54	-	-	-	-	27.213	133.854	191.826	284.161	0.584	0.845	0.890	1.021
		0	4	1	0	2.240	0.770	0.589	0.938								
Korea	AC	0.97	0.93	0.94	0.91	-	-	-	-	6.771	24.332	22.939	5.661	0.416	0.155	0.110	0.021
		8	5	9	2	0.410	0.300	0.548	0.098								

Korea	EI	1.00	0.85	0.87	0.70	-	0.5	0.1	1.6	0.8	-	9.54	20.6	72.8	1.0	1.0	1.0	1.0
		0	5	1	0	98	41	28	81	36	5	47	02	00	00	00	00	
		EF	0.	0.	0.	0.	-	-	-	-	-	-	-	-	-	-	-	-
		F	91	74	69	49	1.4	0.3	2.0	0.9	2.7	18.6	53.5	142.	10.	2.1	2.8	1.9
Luxembourg	EI	4	6	3	7	98	53	25	69	57	85	31	806	409	22	83	65	
		1.	1.	1.	1.	-	-	-	-	-	-	-	-	-	-	-	-	
		AC	09	14	26	41	1.0	0.6	1.3	0.9	2.7	9.14	32.8	70.0	9.4	1.1	1.8	0.9
		T	6	6	1	0	78	72	71	02	93	0	85	03	09	22	83	65
Mexico	EI	0.	0.	0.	0.	-	-	-	-	-	-	-	-	-	-	-	-	
		91	57	40	33	2.4	1.9	1.0	1.2	0.3	2.02	4.85	8.01	1.0	1.0	1.0	1.0	
		2	9	6	1	49	44	41	20	08	8	2	6	00	00	00	00	
		EF	0.	0.	0.	0.	-	-	-	-	-	-	-	-	-	-	-	-
Netherlands	EI	94	60	38	38	1.9	2.3	1.3	0.5	0.1	1.91	5.09	6.91	0.3	0.9	1.0	0.8	
		4	0	9	4	18	61	92	05	91	1	7	2	18	31	48	67	
		AC	0.	0.	1.	0.	-	-	-	-	-	-	-	-	-	-	-	-
		T	96	96	04	86	0.6	0.4	0.8	2.1	0.1	0.11	0.24	1.10	0.6	0.0	0.0	0.1
New Zealand	EI	4	7	6	2	74	58	44	21	17	7	5	4	82	69	48	33	
		1.	1.	1.	0.	-	-	-	-	-	-	-	-	-	-	-	-	
		05	17	04	97	1.3	0.2	0.8	1.2	3.5	14.0	4.60	3.82	1.0	1.0	1.0	1.0	
		0	6	8	7	33	27	98	95	87	06	1	2	00	00	00	00	
Norway	EI	0.	0.	0.	0.	-	-	-	-	-	-	-	-	-	-	-	-	
		96	99	81	71	0.0	0.5	1.5	1.0	2.5	1.15	24.0	48.5	4.8	0.1	9.1	6.2	
		5	0	4	7	65	92	47	57	51	3	48	25	08	19	66	07	
		AC	1.	1.	1.	1.	-	-	-	-	-	-	-	-	-	-	-	-
Poland	EI	09	18	29	36	1.4	0.4	1.2	0.2	6.1	15.1	28.6	44.7	5.8	1.1	10.	7.2	
		0	8	0	3	08	92	83	07	37	59	50	03	08	19	166	07	
		EF	1.	0.	0.	0.	-	-	-	-	-	-	-	-	-	-	-	-
		F	06	88	74	61	0.7	0.5	1.3	1.3	3.7	7.45	23.2	41.6	1.0	1.0	1.0	1.0
Portugal	EI	9	7	6	8	87	65	22	96	10	4	52	70	00	00	00	00	
		EF	1.	0.	0.	0.	-	-	-	-	-	-	-	-	-	-	-	-
		05	90	76	65	0.6	0.4	1.5	1.0	3.0	6.23	21.3	37.1	0.8	0.7	0.9	0.8	
		6	4	4	1	10	43	24	82	52	3	85	78	18	75	15	94	
Spain	EI	1.	0.	0.	0.	-	-	-	-	-	-	-	-	-	-	-	-	
		01	98	97	94	0.1	0.1	0.2	0.5	0.6	1.22	1.86	4.49	0.1	0.2	0.0	0.1	
		2	1	6	9	89	49	04	53	59	1	7	2	82	25	85	06	
		AC	1.	1.	1.	1.	-	-	-	-	-	-	-	-	-	-	-	-
Sweden	EI	10	26	31	02	1.1	2.3	1.9	1.6	0.7	2.00	3.09	0.33	1.0	1.0	1.0	1.0	
		3	5	2	6	54	54	28	80	18	7	1	9	00	00	00	00	
		EF	1.	1.	1.	0.	-	-	-	-	-	-	-	-	-	-	-	-
		F	09	17	18	98	0.8	1.4	1.6	0.6	0.6	1.35	1.96	0.15	1.2	0.6	0.6	23.
United Kingdom	EI	7	1	9	9	65	14	30	62	76	6	2	1	40	51	21	411	
		AC	1.	1.	1.	1.	-	-	-	-	-	-	-	-	-	-	-	-
		T	00	07	10	03	0.2	0.7	0.1	0.9	0.0	0.65	1.12	0.49	0.2	0.3	0.3	24.
		5	9	3	8	64	18	14	56	42	0	9	0	40	49	79	411	
United States	EI	0.	0.	0.	0.	-	-	-	-	-	-	-	-	-	-	-	-	
		94	83	72	61	1.1	0.3	1.5	0.6	1.1	4.03	9.84	16.6	1.0	1.0	1.0	1.0	
		3	8	2	6	66	88	17	43	27	3	7	50	00	00	00	00	
		EF	0.	0.	0.	0.	-	-	-	-	-	-	-	-	-	-	-	-
Vietnam	EI	92	81	67	60	1.4	0.8	1.0	0.5	1.5	4.82	11.6	17.1	1.4	1.1	1.2	1.0	
		0	1	8	7	01	11	42	10	97	5	08	38	76	80	13	30	
		AC	1.	1.	1.	1.	-	-	-	-	-	-	-	-	-	-	-	-
		T	02	03	06	01	0.2	0.5	0.5	0.2	0.4	0.79	1.76	0.48	0.4	0.1	0.2	0.0
Yemen	EI	5	5	3	4	78	92	84	00	70	1	1	7	76	80	13	30	
		0.	0.	0.	0.	-	-	-	-	-	-	-	-	-	-	-	-	-
		95	88	60	40	0.3	1.8	3.2	1.2	4.3	9.95	49.4	112.	1.0	1.0	1.0	1.0	
		5	9	2	0	21	29	27	81	68	2	68	841	00	00	00	00	
Zimbabwe	EI	0.	0.	0.	0.	-	-	-	-	-	-	-	-	-	-	-	-	
		95	89	49	34	0.4	3.3	2.5	0.8	4.3	10.2	67.7	131.	1.0	0.9	1.4	1.1	
		6	3	3	3	63	75	89	99	10	64	96	497	81	50	51	71	
		AC	0.	1.	1.	1.	-	-	-	-	-	-	-	-	-	-	-	-
Australia	EI	99	01	21	16	0.1	2.2	0.1	0.6	0.0	0.31	18.3	18.6	0.0	0.0	0.4	0.1	
		9	1	9	7	35	01	27	45	58	3	27	57	81	50	51	71	
		EF	1.	1.	1.	1.	-	-	-	-	-	-	-	-	-	-	-	-
		F	02	18	37	26	0.9	1.8	0.9	2.0	0.2	1.97	5.25	4.17	1.0	1.0	1.0	1.0
Brazil	EI	3	8	3	6	03	01	88	88	10	9	1	9	00	00	00	00	
		EF	1.	1.	1.	1.	-	-	-	-	-	-	-	-	-	-	-	-
		01	16	29	14	0.9	1.3	0.2	2.1	0.1	1.71	4.20	2.36	1.2	0.8	0.8	0.5	
		8	0	0	2	49	92	56	26	80	7	5	3	28	39	04	17	
Canada	EI	1.	1.	1.	1.	-	-	-	-	-	-	-	-	-	-	-	-	
		00	02	06	10	0.0	0.3	0.5	0.2	0.0	0.26	1.04	1.81	0.2	0.1	0.1	0.4	
		6	4	5	9	41	30	63	25	30	3	6	6	28	61	96	83	
		AC	1.	1.	1.	0.	-	-	-	-	-	-	-	-	-	-	-	-
France	EI	03	01	08	96	0.0	0.2	0.6	2.1	1.7	0.83	6.90	3.86	1.0	1.0	1.0	1.0	
		3	2	3	3	67	02	93	53	17	7	8	2	00	00	00	00	
		EF	0.	1.	1.	1.	-	-	-	-	-	-	-	-	-	-	-	-
		F	98	01	12	04	0.2	0.8	0.9	2.1	0.7	0.80	10.2	4.81	2.3	0.4	1.4	0.2
Germany	EI	5	0	6	7	54	46	46	12	07	3	67	8	61	30	98	99	
		AC	1.	1.	0.	0.	-	-	-	-	-	-	-	-	-	-	-	-
		T	04	00	96	91	0.3	0.6	0.1	0.1	2.4	0.03	3.35	8.68	3.3	1.4	0.4	0.7
		8	3	2	9	30	33	89	66	24	4	9	0	61	30	98	01	
India	EI	0.	0.	0.	0.	-	-	-	-	-	-	-	-	-	-	-	-	
		94	74	64	46	1.6	0.5	1.9	1.2	2.4	12.1	21.1	41.3	1.0	1.0	1.0	1.0	
		3	5	9	5	79	16	73	02	55	02	44	40	00	00	00	00	
		AC	1.	1.	1.	1.	-	-	-	-	-	-	-	-	-	-	-	-

Switzerland	<i>EF</i>	0.	0.	0.	0.	-	-	-	-	2.9	11.9	23.6	44.9	-	0.9	1.1	1.0
	<i>F</i>	93	74	61	43	1.5	0.4	2.5	1.0	21	89	03	77	0.6	91	09	89
		2	7	9	5	81	43	32	23								
	<i>AC</i>	1.	0.	1.	1.	-	-	-	-	-	0.11	2.45	3.63	1.6	0.0	0.1	0.0
	<i>T</i>	01	99	05	07	0.1	0.1	0.9	0.2	0.4	3	9	7	68	09	09	89
		2	7	2	0	19	02	98	37	66							
	<i>EI</i>	0.	0.	0.	0.	-	-	-	-	0.0	0.98	2.95	8.08	1.0	1.0	1.0	1.0
		99	95	87	72	0.5	0.1	0.7	1.8	26	0	7	3	00	00	00	00
		9	2	4	3	44	63	31	91								
	<i>EF</i>	0.	0.	0.	0.	-	-	-	-	0.1	1.30	3.33	7.73	0.8	1.0	1.1	0.9
	<i>F</i>	99	93	85	73	0.6	0.3	0.4	1.7	54	4	3	0	03	05	55	58
		2	7	8	3	49	08	94	54								
Turkey	<i>AC</i>	1.	1.	1.	0.	-	-	-	-	-	-	-	-	-	-	-	-
	<i>T</i>	00	01	01	98	0.1	0.1	0.2	0.2	0.1	0.32	0.37	0.35	0.1	0.0	0.1	0.0
		7	7	8	6	14	66	64	06	28	4	5	2	97	05	55	42
	<i>EI</i>	1.	1.	1.	1.	-	-	-	-	-	-	-	-	-	-	-	-
		11	11	09	01	1.4	0.8	0.1	0.4	2.9	3.82	4.91	1.15	1.0	1.0	1.0	1.0
		7	1	3	6	83	28	77	36	08	4	9	1	00	00	00	00
	<i>EF</i>	1.	1.	0.	0.	-	-	-	-	-	-	-	-	-	-	-	-
	<i>F</i>	06	01	96	87	0.4	0.5	0.7	0.5	1.4	0.60	1.97	12.0	0.5	0.0	0.4	5.9
		1	7	8	1	01	83	29	84	34	1	2	37	82	95	93	00
	<i>AC</i>	1.	1.	1.	1.	-	-	-	-	-	-	-	-	-	-	-	-
	<i>T</i>	05	09	13	16	1.0	0.1	0.6	0.2	1.4	3.22	6.89	13.1	0.4	0.9	1.4	6.9
		5	2	0	6	37	82	89	96	74	2	1	88	18	05	93	00
UK	<i>EI</i>	0.	0.	0.	0.	-	-	-	-	-	-	-	-	-	-	-	-
		89	69	57	41	1.9	1.1	1.4	1.3	19.	68.0	125.	213.	1.0	1.0	1.0	1.0
		7	7	6	6	67	04	69	06	729	08	920	611	00	00	00	00
	<i>EF</i>	0.	0.	0.	0.	-	-	-	-	-	-	-	-	-	-	-	-
	<i>F</i>	91	72	57	44	1.6	1.1	1.5	1.0	16.	60.4	125.	194.	0.8	0.8	0.9	0.9
		3	5	7	9	82	96	45	20	450	24	501	779	51	86	97	14
	<i>AC</i>	0.	0.	0.	0.	-	-	-	-	-	-	-	-	-	-	-	-
	<i>T</i>	98	96	99	92	0.3	0.0	0.0	0.7	3.2	7.58	0.41	18.8	0.1	0.1	0.0	0.0
		2	0	8	5	49	68	55	77	79	4	9	32	49	14	03	86
	<i>EI</i>	0.	0.	0.	0.	-	-	-	-	-	-	-	-	-	-	-	-
		88	61	49	39	2.3	1.7	0.9	0.7	224	904.	170	256	1.0	1.0	1.0	1.0
		2	7	1	5	48	23	75	49	.32	692	4.79	4.77	00	00	00	00
US	<i>EF</i>	0.	0.	0.	0.	-	-	-	-	-	-	-	-	-	-	-	-
	<i>F</i>	88	64	50	39	2.1	1.7	1.0	0.9	211	819.	162	254	1.2	0.9	0.9	0.9
		7	6	8	8	10	11	80	33	.51	307	3.69	8.01	32	04	53	92
	<i>AC</i>	0.	0.	0.	0.	-	-	-	-	-	-	-	-	-	-	-	-
	<i>T</i>	99	95	96	99	0.3	0.1	0.1	0.4	12.	85.3	81.1	16.7	0.2	0.0	0.0	0.0
		3	5	7	4	10	22	17	23	814	85	07	59	32	96	47	08

Highlights

- We use index decomposition analysis to derive the true energy efficiency level
- We use econometric models to examine the impact of energy efficiency on CO₂ emissions
- We account for both economic and noneconomic factors such as lifestyle and behaviour
- Energy efficiency makes a relative bigger contribution to driving down CO₂ emissions
- Noneconomic factors also exert a non-trivial influence on CO₂ emissions

ACCEPTED MANUSCRIPT