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Energy diversification, financial development and economic development: an examination of convergence in OECD countries

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Abstract

Purpose – This study examines the convergence of energy diversification, financial development and per-capita income in OECD countries.

Design/methodology/approach – The research employs the club convergence test to assess convergence among OECD countries and uses Granger causality tests and panel regressions to identify the determinants of convergence, using data from 1997 to 2021.

Findings – The convergence tests showed no overall convergence but revealed convergence clubs for each factor. Granger causality tests indicated short-run bi-directional relationships between the variables. Long-run panel regression analysis confirmed that technological progress significantly improves per capita income and energy diversification. Additionally, it revealed bi-directional relationships between energy diversification and financial development, a uni-directional relationship from financial development to per capita income and a U-shaped effect of per capita income on energy diversification, with a turning point at $67,112.8 per year.

Practical implications – The findings suggest that within each convergence club, implementing microeconomic incentives for technology development and diffusion in energy, production and financial services could help lagging countries catch up.

Originality/value – This study pioneers the testing of convergence in energy diversification, financial development and per capita income in OECD countries and identifies the determinants of this convergence.

Keywords Convergence, Panel data, Energy diversification, Financial development, Economic development, OECD

Paper type Research paper

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1. Introduction

Convergence theory, first introduced by Galor (1996) and later refined by Barro and Sala-i-Martin (1992), suggests that less affluent economies, driven by diminishing marginal returns, tend to catch up with wealthier counterparts over time. This convergence is facilitated by common factors like technological advancements, investment, and saving rates. In integrated markets, where technology is widely accessible, convergence becomes more achievable.

Technological progress has been a primary driver of economic growth since the 1990s (McMillan *et al.*, 2014). As income levels rise, societies shift focus from meeting basic needs to addressing environmental concerns. Energy, a crucial input for production, sees increased demand as economic output grows [1]. Financial development, which provides resources for investments and production, further drives economic activities, thereby amplifying energy demand (Shahbaz *et al.*, 2018).

However, reliance on non-renewable sources like coal, oil, and natural gas leads to CO2 emissions, accelerating climate change. In contrast, renewable energy sources like solar, wind, biomass, hydropower, and geothermal offer cleaner alternatives, though their effectiveness is often constrained by factors like weather dependency and lower efficiency. Therefore, energy diversification – shifting from fossil fuels to renewables – is essential to achieve a balance between economic growth and environmental sustainability.

Since the 1990s, technological progress has facilitated the shift from fossil fuels to renewables in energy production (Paramati *et al.*, 2022). Despite the faster growth rate of renewable energy consumption (3.37% annually from 1980 to 2022) compared to total energy consumption (1.91%), renewables accounted for just 6.25% of global energy consumption by 2022. In contrast, coal, natural gas, oil, and nuclear energy made up 32.30%, 24.76%, 32.43%, and 4.48%, respectively [2]. This highlights the need to boost renewables in the energy mix to enhance diversification.

Energy diversification not only stabilizes supply and prices but also influences economic performance and financial development. Advanced financial systems are crucial for financing clean energy projects and facilitating economic growth, thereby driving energy diversification. Meanwhile, technological progress transforms production processes, financial services, and energy sources, and globalization fosters the exchange of technology, capital, and information. However, the pace of change in energy diversification, per-capita income, and financial development varies significantly by country, largely due to resource availability and differing levels of technology diffusion. Understanding the convergence of these variables can inform policies for sustainable development goals.

Previous studies, including those by Cabral and Castellanos-Sosa (2019), Zhao and Serieux (2019), Ghatak and De (2021), and Alhassan *et al.* (2022), have examined the convergence of per-capita income and its association with financial development across different regions. However, research on the convergence of energy diversification and its link to economic and financial development remains limited. A few studies, such as Gozgor and Paramati (2022), Yilanci *et al.* (2021), have explored the relationship between energy diversification and economic growth, while others, including Shahbaz *et al.* (2023) and Nibedita and Irfan (2023), have examined the connections between financial development and energy diversification. These studies consistently note a narrowing income gap between countries over time and/or the formation of convergence groups, yet the relationships between energy diversification, per-capita income, and financial development and the role of technological progress remain inconclusive, possibly due to differences in contexts, dataset periods, and techniques used for investigation.

We argue that technological development and diffusion can eventually lead countries to achieve a harmonious balance of per-capita income, financial development, and energy diversification. However, the lack of international cooperation in production, financial services, and energy technology innovation hampers the sharing of R&D knowledge and information, thus slowing technology diffusion (Jørgensen *et al.*, 2018). OECD countries, with their high-income status, advanced technology, robust finance, and sustainable development goals, are well-positioned to accelerate this technology diffusion process through coordinated policies and economic openness.

Therefore, this study addresses two key research questions:

(1) Do energy diversification, per-capita income, and financial development in OECD countries converge over time?

(2) How do interactions between these variables drive convergence in OECD countries?

To address these questions, we analyze data from 38 OECD countries spanning 1997–2021. This period offers comprehensive data on energy diversification, financial development, and per-capita income, while encompassing significant policy shifts and initiatives aimed at promoting sustainability. The late 1990s and early 2000s marked pivotal technological advancements in energy production and financial systems, coupled with growing globalization and economic integration among OECD nations (Kurniawati, 2020). These factors make the timeframe ideal for examining convergence, as it reflects both technological diffusion and policy impacts on the studied variables.

Our study makes several contributions to the literature. First, it is the first to test convergence across energy diversification, financial development, and per-capita income within OECD countries. While earlier research has focused on income or financial development convergence in Europe or globally, none has analyzed energy diversification – a critical aspect of sustainable development. Given the OECD's coordinated policies promoting wealth, green initiatives, and financial stability, our findings offer insights into how advanced technologies and practices diffuse across member nations, helping policymakers enhance collaboration and technology-sharing efforts. Second, we apply the log-t convergence test by Phillips and Sul (2007, 2009), a more advanced method for analyzing heterogeneous panel data. Unlike traditional β- and σ-convergence tests, which assume uniform growth paths across countries, the log-t test accommodates individual growth trajectories while assessing overall and club convergence. Lastly, we examine the interrelationships between energy diversification, financial development, and per-capita income using updated panel data. This provides insights into how these factors interact to drive convergence. Previous studies have largely explored the links between energy consumption and either economic growth or financial development using global or European datasets. By narrowing the focus to OECD countries, our research delivers a deeper understanding of these dynamics, contributing valuable perspectives to discussions on sustainable economic development.

The paper is structured as follows: Section 2 offers a comprehensive review of the literature. Section 3 outlines the methodologies used and provides an overview of the data. Section 4 presents the empirical results. Finally, Section 5 concludes the study, highlighting its policy implications.

2. Literature review

2.1 Convergence

Despite sharing traits such as high income, advanced technology, strong financial systems, and sustainable development policies, OECD countries display significant disparities in energy diversification, financial development, and per-capita income. For instance, in 2021, Slovakia had an energy concentration index of 0.0468, while Costa Rica's was 0.4203. Per-capita GDP ranged from US$6,423.86 in Colombia to US$110,425.89 in Luxembourg, and the financial development index varied from 0.2524 in Estonia to 0.9392 in Switzerland. Over the 1997–2021 period, these disparities have narrowed, with standard deviations decreasing. This raises the question of whether energy diversification, financial development, and per-capita income in OECD countries are converging over time.

2.1.1 Methods for testing convergence. Several methods are used to test convergence, including β-convergence, σ-convergence, stochastic convergence, and log-t convergence.

β-convergence examines whether countries with lower initial levels grow faster, while σ-convergence looks at whether disparities decrease over time. Stochastic convergence assesses whether shocks to a variable are temporary. However, β and σ-convergence tests rely on restrictive assumptions that countries follow the same growth path. In contrast, log t convergence, developed by Phillips and Sul (2007, 2009), allows for individual transition paths and can identify both overall and club convergence. This method is widely used in economics and energy studies (Tomal, 2023).

2.1.2 Energy diversification. Technological advancements, such as artificial intelligence, have expanded opportunities for energy diversification (Zhang *et al.*, 2024; Zhao *et al.*, 2024), potentially facilitating convergence among OECD countries. While no studies have directly examined the convergence in energy diversification, related research on renewable energy offers insights. Reboredo (2015) found no log t convergence in renewable energy shares, while Demir and Cergibozan (2020) observed β-convergence in alternative energy consumption within OECD countries.

Global and regional studies provide mixed findings. Bigerna *et al.* (2021) and Berk *et al.* (2020) found σ- and β-convergence in renewable energy shares globally and within the EU. However, Saba and Ngepah (2022b) and Saba and Ngepah (2022a) reported no log t convergence but identified convergence clubs. Pinar (2024) also found no global convergence in renewable energy innovation but noted the formation of two convergence clubs.

2.1.3 Financial development. Technological advancements in finance have driven financial development (Khan *et al.*, 2024; Misati *et al.*, 2024), potentially promoting convergence within OECD countries. However, studies on financial development convergence among OECD countries remain limited. Narayan *et al.* (2011) identified β-convergence in stock market growth among less developed OECD members. Maxfield *et al.* (2017) found no log t convergence in financial leverage but observed convergence among large transnational institutions in OECD countries.

Globally or within regions like Europe, several studies often indicate β-convergence. For example, Fung (2009) and Stolbov and Veysov (2011) reported β-convergence in financial depth globally, Affinito (2011) identified it for institutional deposits and loans in Europe. However, studies allowing for individual growth paths suggest convergence clubs rather than uniform convergence. For instance, Niţoi and Pochea (2016) observed no log t convergence for various financial indicators in Central and Eastern Europe, while Cavallaro and Villani (2021) observed similar findings in European financial development indices, suggesting that technology alone cannot ensure uniform financial convergence across OECD countries.

2.1.4 Per-capita income. Technological innovation has been linked to economic growth (Cheng *et al.*, 2021; Khan *et al.*, 2024), and several studies show β and stochastic convergence in per-capita income across OECD countries. Greta and Lewandowski (2015) and Margaritis *et al.* (2007) found evidence of β-convergence, while King and Ramlogan-Dobson (2014) identified stochastic convergence to the U.S. for half of OECD countries, and Kónya (2023) found it for all OECD nations.

Few studies have used the log-t convergence test for per-capita GDP in OECD countries. Research using broader samples, such as Cavallaro and Villani (2021), Mazzola and Pizzuto (2020), and von Lyncker and Thoennessen (2017), found no log t convergence and the formation of convergence clubs.

2.1.5 Hypothesis construction. The literature suggests β-convergence, a lack of global log t convergence, and the formation of convergence clubs for energy diversification, financial development, and per-capita income among OECD countries. This implies that technological advancements may promote convergence but cannot guarantee uniform growth rates due to varying benefits across countries. Therefore, the hypothesis is:

H1. There is no overall convergence in energy diversification, financial development, and per-capita income among OECD countries, but convergence clubs may emerge in these areas.

2.2 Relationships

Promoting energy diversification is crucial, going beyond just increasing renewable energy, though adding more renewables is key. While substantial research explores the relationships between economic growth, financial development, and renewable energy across various regions, few studies focus on how energy diversification interacts with economic or financial development, particularly within OECD countries. This section reviews the relevant literature on the interplay between energy diversification, economic development, and financial development.

2.2.1 Energy diversification and economic development. 2.2.1.1 Impact of energy diversification on economic growth. Energy resources are unevenly distributed globally, leading to varying degrees of energy diversification across countries. Many nations rely on specific energy sources due to cost advantages, which can limit diversification. Overdependence on a few sources exposes economies to risks from energy price volatility, political tensions, and policy shifts, potentially harming economic growth (Çetin and Kapkaç, 2022). For example, Huntington and Liddle (2022) found that a 10% increase in energy prices reduced growth by 0.15% on average across OECD nations.

Empirical evidence on the effects of energy diversification on economic growth is mixed. Gozgor and Paramati (2022) found that greater energy diversification supports long-term economic growth in G20 economies, though some OECD nations experienced short-term growth declines. Conversely, Ahmed *et al.* (2022) found no significant impact of energy diversification on the economic performance of four Nordic countries. Chen *et al.* (2024) demonstrated that while lower levels of diversification hinder growth in BRICS nations, higher levels foster positive effects.

In OECD countries, fossil fuels still account for over 80% of energy consumption (Hu *et al.*, 2022), prompting efforts to diversify energy sources in line with SDG 7 (Affordable and Clean Energy). This diversification encourages clean energy innovations, attracts investments, and boosts per capita income. Based on these findings, we hypothesize:

H2a. Energy diversification positively impacts economic growth in OECD countries.

2.2.1.2 Impact of economic development on energy diversification. Despite high income levels in many OECD countries, fossil fuels remain dominant due to their affordability, accessibility, and established infrastructure. The *energy ladder theory* (Hosier and Dowd, 1987) and *fuel stacking model* (Masera *et al.*, 2000) suggest that rising income typically shifts economies toward cleaner energy sources, though fossil fuels remain part of the energy mix due to renewable energy's instability and high transition costs.

However, empirical studies show mixed results. Shahbaz *et al.* (2023) found that economic growth reduced energy diversification in Australia from 1995 to 2021. Nibedita and Irfan (2024) observed a U-shaped effect in E7 economies, where initial economic growth led to energy concentration before increasing diversification. In OECD countries, rising per capita income often encourages a continued reliance on fossil fuels, slowing the transition to diversified energy sources. Based on these observations, we hypothesize:

H2b. Per capita income negatively impacts energy diversification in OECD countries.

2.2.2 Energy diversification and financial development. 2.2.2.1 Impact of financial development on energy diversification. Diversifying energy sources through renewable energy is capital-intensive, requiring substantial financing for high initial costs, especially in research and development (Wang *et al.*, 2022). Developed financial markets can ease this transition by providing easier access to debt and equity financing, lowering the cost of capital for renewable energy projects (Acheampong *et al.*, 2020). Consequently, financial development is likely to support energy diversification.

Renewable energy projects face more significant financial challenges than fossil fuel projects. They require larger capital investments, longer payback periods, and higher information costs (Peimani, 2018; Nibedita and Irfan, 2024). Additionally, renewable assets carry greater technology-specific risks and are more difficult to liquidate in bankruptcy situations (Steffen, 2020). These factors can lead to lending hesitation or lending interest rate increases. Consequently, even in well-developed financial markets, renewable projects may struggle to secure financing or face higher capital costs, which can slow down the energy diversification process.

Empirical studies indicate mixed effects. Nibedita and Irfan (2024) found no significant impact in E7 economies, while Shahbaz *et al.* (2023) reported positive effects in Australia, driven by government initiatives promoting clean energy. Limi (2020) observed positive effects in sub-Saharan Africa, while Qamruzzaman (2022) noted varying effects in countries like Brazil, South Africa, Russia, India, and China.

OECD countries, with their advanced financial systems, often lead international efforts in renewable energy innovation, as seen in the 2015 Paris Agreement (Jørgensen *et al.*, 2018). Aligning with the findings of Shahbaz *et al*. (2023) in Australia, we hypothesize:

H3a. Financial development positively impacts energy diversification in OECD countries.

2.2.2.2 Impact of energy diversification on financial development. Energy diversification, particularly through renewables, requires significant financing at every stage—from research and development to infrastructure and ongoing operations. This capital demand has led to the creation of specialized financial products, such as green bonds and loans, to facilitate renewable energy investment (Azhgaliyeva *et al.*, 2020; Alharbi *et al.*, 2023). Such diversification can attract international financial institutions and sustainable investors, enhancing the depth and resilience of the financial system (Zhe *et al.*, 2021). Additionally, energy diversification can boost economic stability by reducing energy price volatility and improving energy security, which in turn increases demand for financial services (Hache, 2018; Maciejowska, 2020).

However, risks accompany energy diversification. Renewable energy projects face challenges like technological underperformance, inconsistent resource availability (e.g. limited sunlight or wind), and changing regulations, which could lead to financial losses. These risks may result in loan defaults and erode investor confidence, straining financial institutions.

Although no studies directly link energy diversification to financial development, research on renewable energy consumption generally shows positive effects. Zhe *et al.* (2021) found that expanding renewable energy in Turkey spurred financial sector growth, while Khan *et al.* (2020) observed similar global impacts, linking renewable energy to financial innovation and market expansion.

In OECD countries, policies such as subsidies, tax incentives, and regulations lower investment risks and attract private capital to renewable energy projects. This environment fosters financial innovations tailored to renewables, driving growth in the financial sector. Therefore, we hypothesize:

H3b. Energy diversification positively impacts financial development in OECD countries.

2.2.3 Financial development and economic development. 2.2.3.1 Impact of economic growth on financial development. The demand-following hypothesis (Robinson, 1952) suggests that economic growth drives the development of the financial sector. As economies grow, the need for more sophisticated financial products arises to support business activities and manage risks, encouraging innovation in financial services.

Empirical evidence of this relationship is mixed. Studies like those by Dar and Nain (2023) in South Asia and Atil *et al.* (2020) in Pakistan support the demand-following hypothesis, showing that economic growth fosters financial sector development. However, research by Cherif and Dreger (2016) in MENA countries and Nain and Kamaiah (2014) in India suggests that economic growth does not always lead to financial development, indicating that country-specific factors can influence this dynamic.

OECD countries, with their high-income levels and advanced financial systems, offer a unique environment. Rising incomes enhance savings and investment capacities, driving demand for complex financial products. Their established financial institutions are also well-positioned to innovate and meet this demand.

Thus, we propose the following hypothesis:

H4a. Economic development promotes financial development in OECD countries.

2.2.3.2 Impact of financial development on economic growth. The supply-leading hypothesis argues that financial development is a key driver of economic growth. A well-developed financial system fosters innovation by funding transformative ideas and technological advancements, which increase both the quality and quantity of output (Schumpeter and Opie, 1934). Additionally, an efficient financial system channels savings into productive investments, promoting economic expansion (Bencivenga and Smith, 1991; King and Levine, 1993). In this view, financial development acts as a catalyst for sustained economic progress.

Empirical evidence largely supports this hypothesis. Studies on OECD countries by Aydin and Malcioglu (2016), Madsen and Ang (2016), Purewal and Haini (2022), Çetin and Çınar (2023), and Hashemizadeh *et al.* (2023) all show that financial development positively influences economic growth. With well-regulated financial markets, OECD countries effectively allocate resources to productive investments, fostering long-term economic growth.

Therefore, we hypothesize:

H4b. Financial development promotes economic growth in OECD countries.

3. Methodology and data

3.1 Energy diversification, financial development and per-capita income variables

Energy diversification is the process of shifting from heavy reliance on one energy source to a more balanced mix. Energy comes from five primary sources: coal, natural gas, petroleum, nuclear, and renewables. To gauge diversification, we use the Herfindahl-Hirschman Index (HHI), termed the *Energy HHI*. Traditionally employed to measure the concentration of companies' market shares, the HHI approach has been extended to gauge the concentration of export markets by the World Bank [3] and to measure energy diversification by researchers such as Gozgor and Paramati (2022), Akrofi (2021) and Shahbaz *et al.* (2023). The *Energy HHI* for country i in year t is

$$Energy\,HHI_i = \frac{\sum_{j=1}^{n_i}\left(\frac{e_{ij}}{E_i}\right)^2 - \frac{1}{n_i}}{1-\frac{1}{n_i}} \qquad (1)$$

In Eq. (1), E_i represents the total primary energy consumption of country i. e_{ij} denotes the amount of energy consumption from source j by country i, while n_i represents the number of energy sources consumed by country i. The *Energy HHI* falls within the range of 0–1, with a higher value indicating greater concentration and lower energy diversification. This index helps assess whether a country's energy portfolio has diversified over time and enables cross-country comparisons.

Financial development refers to improvements in financial markets and institutions. Pei *et al.* (2023) and Song *et al.* (2021) suggest using proxies like private credit to GDP ratio and market capitalization to GDP ratio, but these may not capture the full picture. We follow

Ngo *et al.* (2022), Acheampong *et al.* (2020), Lahiani *et al.* (2021), and Baloch *et al.* (2021), utilizing IMF's financial development indices constructed from 20 indicators, with the construction method detailed by Svirydzenka (2016). Our primary proxy is the overall *Financial Dev index*, supplemented by the financial institution index (*FI Dev*) and financial market index (*FM Dev*), ranging from 0 to 1, with higher values indicating greater development.

Per-capita income, reflecting individual economic well-being, is measured using per-capita GDP.

3.2 Convergence

3.2.1 Beta convergence. Beta convergence tests whether countries with lower energy diversification, financial development, or per-capita income grow faster than those with higher levels using the following equation:

$$ln\left(\frac{y_{it}}{y_{it-1}}\right) = \beta\, ln(y_{it-1}) + \epsilon_{it} \tag{1}$$

where y_{it} represents the set including energy diversification, financial development, and per-capita income. A negative and statistically significant parameter β indicates beta convergence.

3.2.2 Sigma convergence. Sigma convergence assesses whether the gaps in energy diversification, financial development, or per-capita income levels among countries narrow over time, as shown in equation:

$$ln\left(\frac{w_{it}}{w_{it-1}}\right) = \sigma\, ln(w_{it-1}) + \epsilon_{it} \tag{2}$$

where $w_{it} = ln\, y_{it} - {}^{1}/_{n} \sum_{i=1}^{n} y_{it}$. Sigma convergence is confirmed if σ is negative and statistically significant.

We employ a fixed-effects estimator for Eqs.(1)-(2) and verify the results' robustness using a random-effects estimator.

3.2.3 Gamma (log t) club convergence. Phillips and Sul (2007) propose log-t convergence test, which captures the heterogeneity in panel data X_{it} through a common factor μ_t, and idiosyncratic effects δ_{it} and ε_{it}, using the following single-factor model:

$$X_{it} = \delta_{it}\mu_t + \varepsilon_{it} \tag{3}$$

Where X_{it} is the growth rate of the variables of interest for country *i* in year *t*; μ_t is the common factor μ_t, which we interpret as the common technology available to all OECD countries; δ_{it} is the idiosyncratic distance between the common factor μ_t and the systemic part of X_{it} for country *i* in year t, reflecting the individual growth factor of country *i*; ε_{it} is the random shocks.

Convergence occurs when the individual growth factor δ_{it} converges.

Assume that the common factor μ_t is captured by the average growth rate of all countries in any year, δ_{it} can be isolated by taking the ratio of a growth rate of a country and the average rate. The relative transition parameter (h_{it}), which measures the performance of country *i* (δ_{it}) relative to the common growth rate (μ_t) in year *t*, and the mean square of relative transition differences (H_t) are defined as:

$$h_{it} = \frac{X_{it}}{{}^{1}/_{n}\sum_{i=1}^{n} X_{it}} = \frac{\delta_{it}}{{}^{1}/_{n}\sum_{i=1}^{n} \delta_{it}} \tag{4}$$

$$H_t = \frac{1}{n}\sum_{i=1}^{N}(h_{it} - 1)^2 \qquad (5)$$

The cross-sectional mean of h_{it} is 1. The overall convergence of all countries occurs in the long run ($t \to \infty$) when h_{it} converge to 1, leading to H_t converging to 0. This convergence coincides with δ_{it} converge to δ_t. As $t \to \infty$, if H_t remains positive, it implies that the growth rates of all countries diverge or some countries converge despite divergence occurring among others.

To formulate an econometric test for the time-varying idiosyncratic components δ_{it}, Phillips and Sul (2007) model δ_{it} as:

$$\delta_{it} = \delta_i + \sigma_i \xi_{it} L(t)^{-1} t^{-\alpha} \qquad (6)$$

where δ_i is time-invariant growth factor for country i; $\xi_{it} \sim iid(0, 1)$ across i but weakly dependent on t; and $L(t)$ is a slowly varying function (like log t) and $L(t)^{-1}$ is a slowly decay function for which $L(t) \to \infty$ and then $L(t)^{-1} \to 0$ as $t \to \infty$; σ_i is an idiosyncratic scale parameter; and $\alpha \geq 0$ is the decay rate.

The null and alternative hypotheses are:

H_0: $\delta_{it} = \delta$ for all i and/or $\alpha \geq 0$ (overall convergence)

H_1: $\delta_{it} \neq \delta$ for some i and/or $\alpha < 0$ (divergence)

The null hypothesis of convergence is tested using the following log t regression:

$$ln\left(\frac{H_1}{H_t}\right) - 2\log L(t) = \theta + \gamma \, log\, t + u_t \qquad (7)$$

where $L(t) = log(t + 1)$; $\gamma = 2\alpha$, measuring the convergence speed of δ; u_t is the random error.

If the null hypothesis of overall convergence is rejected (i.e. $\gamma = 2\alpha < 0$ at 5% significance level, $t_\gamma < -1.65$), the test for convergence clubs can be tested using the following club convergence algorithm:

(1) Step 1: list sample countries in the ascending order of growth rate in the last year.

(2) Step 2: form a core group of k* countries with the highest growth rates to form a convergence club. The optimal size of a convergence club is determined by maximizing t_k using k countries ($2 \leq k < n$) subject to $min\{t_k\} > -1.65$.

(3) Step 3: Add one country to the core group at a time and run the log t convergence test. If $t_\gamma > -1.65$, the country is included. The core group and the included countries will form the first convergence club.

(4) Step 4: Conduct log t convergence test for the non-included countries. If $t_\gamma > -1.65$, they form the second convergence club. If not, repeat Steps 1–3 to detect sub-convergence clubs. If no core group is formed in Step 2, these countries exhibit divergent behavior.

After identifying the initial convergence clubs, we apply Phillips and Sul (2009)'s club merging test. This test reformulates Phillips and Sul (2007)'s test for adjacent clubs, determining if the adjacent clubs can be merged to form a larger club, and thereby resulting in the final convergence clubs.

We also follow Phillips and Sul (2007, 2009)'s suggestion to employ Christiano and Fitzgerald (2003)'s band pass filter and discard 30% of the data to extract the trend prior to conducting log t convergence tests.

Although the convergence tests can provide evidence of possible convergence clubs, the tests do not explicitly identify the likely drivers for the formation of convergence clubs. This lead us to the next phase of our analysis.

3.3 Interrelationships

We begin by investigating whether the growth of any of the three variables of interest is influenced by its own past growth as well as the past growth of the other two variables using Dumitrescu and Hurlin (2012)'s Granger causality procedure as follows:

$$y_{i,t} = \alpha_i + \sum_{k=1}^{K} \gamma_i^{(k)} y_{i,t-k} + \sum_{k=1}^{K} \beta_i^{(k)} x_{i,t-k} + \epsilon_{i,t} \tag{8}$$

where $y_{i,t}$ represents one of the three variables of interest for country i in year t; $x_{i,t}$ denotes one of the two remaining variables for country i in year t; $\epsilon_{i,t}$ signifies the stochastic error term; the optimal lag orders k are determined using the Akaike information criterion; and $\alpha_i, \beta_i, \gamma_i$ are parameters to be estimated. This Granger model can be estimated for stationary variables, and thus, the stationarity of the variables (in both level and difference forms) needs to be tested before estimation. We conclude x Granger causes y if the coefficients $\beta_i^{(k)}$ collectively show statistical significance different from zero.

We proceed to examine the causal relationships while considering the controlling covariates:

$$y_{i,t} = \beta_0 + \beta_1 trend + \beta_2 x_{i,t-1} + \beta_3 Z_{i,t} + \mu_i + \varepsilon_{i,t} \tag{9}$$

where $y_{i,t}$ and $x_{i,t}$ retain their definitions from Eq. (8); *trend* denotes the linear trend in $y_{i,t}$ from 1997 to 2021, proxied for technological progress; $Z_{i,t}$ is a set of controlling covariates; μ_i represents country-specific unobserved features; $\varepsilon_{i,t}$ represents the random error component; β are parameters to be estimated; all variables, except *trend*, are expressed in natural logarithms.

We select $Z_{i,t}$ based on existing literature and data availability. When $y_{i,t}$ is per-capita income, following studies by Gozgor and Paramati (2022) and Ahmed *et al.* (2022), $Z_{i,t}$ includes fixed capital formation, labor participation, and international trade. When $y_{i,t}$ is financial development, $Z_{i,t}$ incorporates fixed capital formation, unemployment rate, and human development index (HDI), as shown in studies by Ngo *et al.* (2022), Ngoc *et al.* (2024), and Raifu *et al.* (2023). When $y_{i,t}$ is energy diversification, $Z_{i,t}$ comprises oil price and environmental perception (proxied by HDI). This choice is informed by the significant contribution of oil-based energies to CO2 emissions (about 51% of the energy mix) and the reflection of environmental awareness in HDI scores.

The estimator for Eq. (9) is chosen through various tests, including the Breusch-Pagan, Hausman, and *F*-tests. We determine the standard error for the estimator through multiple tests, such as the Modified Wald test for heteroskedasticity, the Pesaran test for cross-sectional dependence, and the Wooldridge test for autocorrelation.

3.4 Data

The dataset comprises a balanced panel spanning 38 OECD countries from 1997 to 2021 (see Appendix). Table 1 presents key statistics and data sources, revealing notable variations among countries for each variable. Notably, the Trend column, serving as a proxy for technological progress, indicates a yearly decrease of 0.2 points in energy source concentration (signaling increased diversification), a $431.9 per year increase (constant 2015) in per-capita GDP, and a 0.3-point annual enhancement in financial development. These positive trends suggest that technological progress could drive countries towards convergence in energy diversification, financial development, and per-capita income. Additionally, we

Table 1. Summary statistics of the deployed variables

Variables	Mean	SD	Min	Max	Trend	Source
HHI energy	0.178	0.094	0.031	0.540	−0.002***	https://www.eia.gov/
Income per capita	33218.37	21837.10	3953.73	112417.88	431.91***	https://databank.worldbank.org/source/world-development-indicators
Financial dev index	0.598	0.217	0.124	1.000	0.003***	https://data.imf.org/
FI dev index	0.662	0.196	0.081	1.000	0.003***	
FM index	0.511	0.265	0.018	1.000	0.003**	
Control variables						
Oil Price	58.852	26.382	14.368	99.565	1.922***	https://alfred.stlouisfed.org
HDI	0.867	0.064	0.638	0.965	0.004***	http://hdr.undp.org/
Unemployment	7.671	4.041	1.810	27.690	−0.041**	https://databank.worldbank.org/source/world-development-indicators
Capital formation	22.831	4.066	10.687	54.274	−0.078***	
Labor participation	60.431	5.557	45.520	78.548	0.062**	
Int'l trade	91.304	53.713	18.126	393.141	1.290***	

Note(s): *** and **: 1% and 5% levels of significance, respectively
Source(s): Authors' work

observe positive growth rates in oil prices, the human development index, labor participation, employment rate, and international trade. However, there is a negative growth rate in gross fixed capital formation to GDP.

4. Empirical results

4.1 Convergence

Table 2 displays the results of β-convergence, σ-convergence, and log t convergence tests for our panel of 38 OECD countries from 1997 to 2021, using the fixed-effects estimator. We find that the β and σ coefficients are all negative and statistically significant at the 1% level. This indicates that energy diversification, per-capita income, and financial development across the OECD countries tend to move towards a common level, while the dispersion in these variables decreases.

However, the t-statistic values of the log-t convergence test are all below −1.65, so the null hypothesis of panel convergence is rejected, suggesting that the 38 OECD countries are not

Table 2. Beta, sigma and log t convergence tests

Tests		Energy HHI	Per-capita income	Financial dev	FI dev	FM dev
Beta	Coef	−0.163***	−0.048***	−0.172***	−0.106***	−0.297***
	Std. err	(0.018)	(0.007)	(0.015)	(0.013)	(0.023)
Sigma	Coef	−0.186***	−0.024***	−0.169***	−0.109***	−0.278***
	Std. err	(0.019)	(0.008)	(0.018)	(0.015)	(0.024)
Log t	Coef	−0.549	−0.440	−0.666	−0.200	−0.680
	t-stat	−12.484	−42.002	−16.700	−4.709	−12.492

Note(s): ***: 1% level of significance, respectively
Source(s): Authors' work

converging to the same steady state regarding energy diversification, financial development, and per-capita income. The discrepancy in convergence results among these tests may stem from their underlying assumptions: β-convergence and σ-convergence assume the same growth path for all countries, whereas the log t convergence allows for individualized transition paths.

Phillips and Sul (2007) suggest that the lack of overall convergence might stem from divergent members within a group. To explore this, we utilize their clustering algorithm to classify countries into converging or divergent clusters. Table 3 outlines the results, with the number of countries in each club detailed in the first column. Using Phillips and Sul's (2009) club merging algorithm, we then investigate potential merges of adjacent clubs, presented in the second column. The final convergence clubs, after both initial classification and merging, are shown in the last column.

For energy diversification, initial classification yields four convergence clubs. Merging Clubs 2 and 3 reduces the final clubs to three. Despite varying levels of energy diversification, OECD countries in these final clubs exhibit convergence, with a strong convergence speed in final Clubs 1 and 3 and a weak speed in final Club 2, as indicated by the log coefficients. Regarding per-capita income, six initial convergence clubs are identified. Merging Clubs 2, 3, and 4 results in four final clubs, showing varying convergence speeds.

Initial classification uncovers four clubs for overall financial development, which are reduced to three after merging. The final clubs exhibit varying speeds of convergence. Additionally, two convergence clubs emerge for financial institution development, while four clubs are identified for financial market development. The merging tests reject club merging for both financial development components.

4.2 Interrelationships

4.2.1 Granger causality. The convergence tests in section 4.1 for energy diversification, per-capita income, and financial development are univariate analyses. Now, we investigate potential causal relationships between these variables. Unit root tests, including LLC, Fisher-DF, and Fisher-PP methods, reveal unit roots at the level, particularly with the Breitung test, but reject them at the first difference for all variables (see Table 4). Hence, we employ the Granger causality test for panel data, as proposed by Dumitrescu and Hurlin (2012), at the first difference, with lag selection based on the Akaike Information Criterion (AIC).

Results in Table 5 demonstrate the rejection of the null hypothesis of no association between the lag of one outcome and the current value of other outcomes. This indicates evidence of a bi-directional Granger causality between energy diversification, per-capita income, and financial development in OECD countries.

4.2.2 Panel regression. We explore the causal relationship between energy diversification, financial development, and per capita GDP while controlling for other factors. Table 6 displays the results for selecting an appropriate estimator for panel data models. The Breusch-Pagan test favors random effects over pooled OLS, while the F-test suggests potential bias in both pooled OLS and random effects estimators due to significant observed and unobserved fixed effects. The Hausman test indicates that fixed effects are more suitable, except for the energy diversification model. Consequently, we employ a fixed-effects estimator to account for unobserved country characteristics.

We then assess the residuals of the fixed effects models for heteroskedasticity, cross-sectional dependence, and autocorrelation. The tests reject the null hypotheses of no heteroskedasticity, cross-sectional dependence, and autocorrelation for the three models, except for cross-sectional dependence in the energy diversification model. Therefore, we utilize the fixed effects estimator with Driscoll and Kraay (1998) standard errors to address these issues. The results are presented in Table 7.

In Table 7, Column 1 presents the main regression results, focusing on overall financial development, while Columns 2 and 3 delve into financial institution and market development.

Table 3. Convergence club classification

Initial club classification				Tests of club merging				Final club classification				
Clubs	Members	Log t	*t*-stat	Clubs	Members	Log t	*t*-stat	Clubs	Members	Log t	*t*-stat	Members
Energy HHI												
Club1	4	0.124	1.209					Final Club1	4	0.124	1.209	Costa Rica, Iceland, Luxembourg, Latvia
Club2	10	−0.021	−0.206	Club1+2	14	−0.299	−3.972	Final Club2	24	−0.083	−1.065	Austria, Belgium, Canada, Czechia, Germany, Denmark, Spain, Estonia, Finland, France, United Kingdom, Greece, Ireland, Italy, Japan, South Korea, Lithuania, Mexico, Netherlands, Norway, New Zealand, Slovenia, Sweden, United States Sweden, United States
Club3	14	0.055	0.730	Club2+3	24	−0.083	−1.065					
Club4	10	0.025	0.269	Club3+4	24	−0.226	−6.596	Final Club3	10	0.025	0.269	Australia, Switzerland, Chile, Colombia, Hungary, Israel, Poland, Portugal, Slovakia, Turkiye
Per-capita income												
Club1	6	−0.018	−0.133					Final Club1	6	−0.018	−0.133	Australia, Switzerland, Ireland, Luxembourg, Norway, United States
Club2	5	0.183	5.285	Club1+2	11	−0.212	−6.725	Final Club2	19	−0.040	−1.399	Austria, Belgium, Canada, Germany, Denmark, Finland, France, United Kingdom, Iceland, Israel, Japan, South Korea, Lithuania, Netherlands, New Zealand, Poland, Slovakia, Sweden, Turkiye
Club3	10	0.071	2.027	Club2+3	15	0.024	0.776					
Club4	4	0.088	2.554	Club3+4	14	0.018	0.572					
Club5	10	0.145	5.279	Club4+5	14	0.047	1.481	Final Club3	10	0.145	5.279	Chile, Costa Rica, Czechia, Spain, Estonia, Hungary, Italy, Latvia, Portugal, Slovenia
Club6	3	0.296	5.029	Club5+6	13	−0.168	−5.264	Final Club4	3	0.296	5.029	Colombia, Greece, Mexico

(*continued*)

Table 3. Continued

Initial club classification				Tests of club merging				Final club classification				
Clubs	Members	Log t	*t*-stat	Clubs	Members	Log t	*t*-stat	Clubs	Members	Log t	*t*-stat	Members
Financial development indices												
Financial dev												
Club1	5	0.631	2.220					Final Club1	5	0.631	2.220	Australia, Canada, Switzerland, Japan, United States
Club2	9	0.054	0.657	Club1+2	14	−0.483	−5.551	Final Club2	24	−0.081	−1.048	Austria, Belgium, Chile, Colombia, Costa Rica, Germany, Denmark, Spain, Finland, France, United Kingdom, Ireland, Israel, Italy, South Korea, Luxembourg, Mexico, Netherlands, Norway, New Zealand, Poland, Portugal, Sweden, Turkiye
Club3	15	0.256	2.295	Club2+3	24	−0.081	−1.048					
Club4	9	−0.184	−1.573	Club3+4	24	−0.355	−5.361	Final Club3	9	−0.184	−1.573	Czechia, Estonia, Greece, Hungary, Iceland, Lithuania, Latvia, Slovakia, Slovenia
FI dev												
Club1	5	0.543	1.777					Final Club1	5	0.543	1.777	Australia, Canada, Switzerland, Japan, United States
Club2	33	0.050	0.877	Club1+2	38	−0.200	−4.709	Final Club2	33	0.050	0.877	Austria, Belgium, Chile, Colombia, Costa Rica, Czechia, Germany, Denmark, Spain, Estonia, Finland, France, United Kingdom, Greece, Hungary, Ireland, Iceland, Israel, Italy, South Korea, Lithuania, Luxembourg, Latvia, Mexico, Netherlands, Norway, New Zealand, Poland, Portugal, Slovakia, Slovenia, Sweden, Turkiye

(*continued*)

Table 3. Continued

Initial club classification				Tests of club merging				Final club classification				
Clubs	Members	Log t	*t*-stat	Clubs	Members	Log t	*t*-stat	Clubs	Members	Log t	*t*-stat	Members
FM dev												
Club1	7	−0.111	−0.566					Final Club1	7	−0.111	−0.566	Australia, Switzerland, Spain, United Kingdom, Italy, Japan, United States
Club2	14	−0.031	−0.289	Club1+2	21	−0.364	−5.792	Final Club2	14	−0.031	−0.289	Canada, Germany, Denmark, Finland, France, Ireland, South Korea, Luxembourg, Netherlands, Norway, New Zealand, Portugal, Sweden, Turkiye
Club3	8	0.187	0.873	Club2+3	22	−0.637	−17.415	Final Club3	8	0.187	0.873	Austria, Belgium, Chile, Colombia, Greece, Israel, Mexico, Poland
Club4	9	0.146	0.994	Club3+4	17	−0.309	−2.988	Final Club4	9	0.146	0.994	Costa Rica, Czechia, Estonia, Hungary, Iceland, Lithuania, Latvia, Slovakia, Slovenia

Source(s): Authors' work

Table 4. Unit root test analysis

Variables	Unit root test methods LLC	Breitung	IPS	Fisher-DF	Fisher-PP
At level					
Energy HHI	−4.45***	0.54	−1.33*	107.21***	131.98***
Per-capita income	−3.65***	0.85	−0.65	95.10*	79.43
Financial dev	−7.20***	−2.16**	−2.07**	112.81***	183.38***
FI dev	−4.91***	0.01	−1.91**	119.72***	144.39***
FM dev	−7.58***	−2.86***	−2.18***	113.31***	165.86***
At first difference					
Energy HHI	−19.19***	−7.25***	−12.93***	409.45***	886.79***
Per-capita income	−13.53***	−2.49***	−5.88***	182.12***	376.41***
Financial dev	−23.45***	−9.76***	−13.51***	446.56***	936.40***
FI dev	−17.72***	−6.37***	−11.44***	373.99***	792.76***
FM dev	−21.66***	−10.32***	−13.91***	459.54***	904.43***

Note(s): The null hypothesis is that the series has a unit root; ***, ** and *: 1%, 5% and 10% levels of
Source(s): Authors' work

Table 5. Dumitrescu and Hurlin (2012) Granger causality test (at difference)

H0: X does not Granger-cause Y H1: X does Granger-cause Y	Coef
Per-capita income → Energy HHI	12.75***
Energy HHI → Per-capita income	10.64***
Financial development → Energy HHI	
Financial dev	13.09***
FI dev	15.17***
FM dev	8.08***
Energy HHI → Financial development	
Financial dev	10.97***
FI dev	17.02***
FM dev	9.74***
Income per capita → Financial development	
Financial dev	10.00***
FI dev	19.56***
FM dev	7.80***
Financial development → Per-capita income	
Financial dev	6.38***
FI dev	9.28***
FM dev	8.44***

Note(s): *: 1% level of significance
Source(s): Authors' work

In the per-capita income model (Part A), a significant and positive *trend* coefficient implies an average annual growth rate of 19.7%, reflecting the positive contribution of technological progress to the formation of convergence clubs for per capita income among OECD countries. However, the negative and statistically insignificant coefficient for one lag of *Energy HHI* suggests a limited impact of energy diversification on per capita income in OECD countries. The positive and significant coefficient for one lag of *Financial Dev* shows the positive

Table 6. Diagnosis tests

Tests	Breusch and Pagan test for random effects			*F*-test for fixed effects			Hausman test for random effects versus fixed effects		
Models	HHI energy	Income per capita	Financial dev	HHI energy	Income per capita	Financial dev	HHI energy	Income per capita	Financial dev
Financial dev	7274.9***	7106.8***	7962.8***	125.2***	403.6***	196.7***	0.7	64.8***	9.9*
FI dev	7026.2***	6307.9***	4747.4***	123.6***	563.2***	69.5***	3.9	58.4***	21.0***
FM dev	7168.1***	8394.4***	8684.9***	121.8***	642.6***	315.0***	2.0	37.2***	12.2**

Tests	Modified Wald test for heteroskedasticity			Pesaran test for cross-sectional dependence			Wooldridge test for autocorrelation		
Models	HHI energy	Income per capita	Financial dev	HHI energy	Income per capita	Financial dev	HHI energy	Income per capita	Financial dev
Financial dev	3456.0***	15713.7***	2637.1***	0.7	5.5***	16.7***	105.7***	160.6***	79.1***
FI dev	3609.8***	21445.1***	20742.3***	0.6	9.0***	2.8***	105.6***	170.6***	29.7***
FM dev	3268.0***	14630.9***	17199.1***	0.6	8.9***	13.9***	107.8***	138.2***	38.0***

Note(s): The table presents the test statistics; *** and **: 1% and 5% levels of significance, respectively
Source(s): Authors' work

Table 7. The interrelationships between energy diversification, financial development, and economic growth

Models	Financial development Financial dev (1) Coef	St. err	FI dev (2) Coef	St. err	FM dev (3) Coef	St. err
Part A: Model per-capita income						
Trend	0.197***	0.026	0.208***	0.019	0.199***	0.030
L1.Log(Energy HHI)	−0.018	0.020	−0.0001	0.021	−0.038*	0.020
L1.Log(Financial dev)	0.339***	0.074	0.312***	0.044	0.006	0.014
Log(Labor participation)	0.984***	0.160	0.956***	0.096	0.897***	0.193
Log(Capital formation)	0.202***	0.024	0.160***	0.034	0.251***	0.031
Log(Intl trade)	0.207***	0.048	0.193***	0.039	0.191***	0.066
Observations	912		912		912	
Part B: Model financial development						
Trend	−0.036	0.029	0.006	0.041	−0.127***	0.038
L1.Log(Per-capita income)	0.013	0.069	−0.087	0.085	0.120	0.104
L1.Log(Energy HHI)	−0.042***	0.013	−0.060***	0.016	−0.038	0.045
Log(HDI)	2.038***	0.224	4.510***	0.747	−0.608	0.388
Log(Unemployment)	−0.020	0.027	−0.017	0.026	0.033	0.046
Log(Capital Formation)	0.111***	0.030	0.218***	0.060	0.232**	0.088
Observations	912		912		912	
Part C: Model energy HHI						
Trend	−0.072***	0.025	−0.071***	0.024	−0.068***	0.024
L1.Log(Financial dev)	−0.141*	0.074	−0.166**	0.064	0.007	0.029
L1.Log(Per-capita income)	0.284*	0.162	0.276*	0.157	0.264	0.157
Log(Oil price)	−0.968***	0.309	−0.937***	0.299	−0.926***	0.300
Log(HDI)	−3.032***	0.575	−2.553***	0.637	−3.285***	0.559
Observations	912		912		912	
Part D: Model energy HHI (L1.Log(Per-capita income)^2 is added)						
Trend	−0.170***	0.047	−0.191***	0.034	−0.113***	0.034
L1.Log(Financial dev)	−0.196**	0.088	−0.226***	0.075	0.004	0.030
L1.Log(Per-capita income)	1.730**	0.647	2.045***	0.536	0.934**	0.447
L1.Log(Per-capita income)^2	−0.075**	0.034	−0.092***	0.031	−0.035	0.024
Log(Oil price)	−2.263***	0.624	−2.510***	0.455	−1.523***	0.454
Log(HDI)	−3.504***	0.653	−2.990***	0.621	−3.553***	0.643
Observations	912		912		912	

Note(s): ***, ** and *: 1%, 5% and 10% levels of significance, respectively; dummy i.Year is dropped for easier viewing
Source(s): Authors' work

influence of financial development on per capita income, with financial institution development exhibiting a stronger effect than financial market development. Additionally, positive and significant coefficients for *Labor Participation*, *Capital Formation*, and *International Trade* indicate their contributions to wealth improvement, aligning with Gozgor and Paramati (2022) and Ahmed *et al.* (2022).

In the financial development model (Part B), the statistically insignificant *trend* coefficient suggests no improvement in OECD countries' financial systems from 1997 to 2021. The insignificant coefficient of one lag of *per capita income* implies a minimal contribution of economic development to financial development. The negative and significant coefficient for one lag of *Energy HHI* indicates a positive influence of energy diversification on financial development. The positive and significant coefficients for *HDI* and *Capital Formation* highlight the positive contribution of human development and physical capital to the development of financial systems in OECD countries, aligning with studies by Ngo *et al.* (2022), Ngoc *et al.* (2024), and Raifu *et al.* (2023).

In the energy diversification model (Part C), the negative and significant *trend* coefficient reflects an annual decline in energy concentration, indicating enhanced diversification. The negative and significant coefficient for one lag of *Financial Dev* suggests that better financial system development fosters improved energy diversification. This relationship is primarily driven by financial institution development, as only the coefficient for *FI Dev* is negative and significant. Rising oil prices and higher human development index also correlate with increased energy diversification. Higher oil prices make fossil fuels less competitive, prompting a shift in investment and consumption towards non-fossil fuel energies. A higher HDI reflects greater awareness of energy security and environmental challenges, leading to more investment and consumption of non-fossil fuel energies, thus enhancing energy diversification.

However, the positive and significant coefficient for *per-capita income* suggests it acts as a barrier to energy diversification. We suspect a non-linear relationship, as suggested by the environmental Kuznets curve framework and Nibedita and Irfan (2024) for E7 economies. Part D confirms this non-linear impact, revealing a U-shaped effect, with the per-capita income turning point of $67,112.8 per year (constant 2015) [4]. Specifically, when per-capita income is below $67,112.8 per year, higher income reduces energy diversification. When per-capita income exceeds $67,112.8 per year, higher income increases energy diversification.

4.3 Discussions of the key findings

Our study first found that, assuming uniform growth, energy diversification, financial development, and per capita income across 38 OECD countries tend to converge toward a common level with decreasing variability. However, when accounting for individual country trajectories, countries do not converge to a single steady state but form distinct convergence clubs—three for energy diversification, three for financial development, and four for per capita income. This supports Hypothesis 1 and aligns with existing literature, such as Saba and Ngepah (2022b) and Saba and Ngepah (2022a) on renewable energy, Niţoi and Pochea (2016) and Cavallaro and Villani (2021) on financial indicators in Europe, and Cavallaro and Villani (2021) and Mazzola and Pizzuto (2020) on per-capita GDP in Europe.

Differences in natural resources, economic incentives, and social structures lead to varied growth paths, underscoring the importance of considering individual trajectories. The lack of overall convergence suggests that countries with lower per capita income, underdeveloped financial systems, and limited energy diversification are not closing the gap with more advanced nations. This could be due to insufficient technology sharing by advanced countries. Nevertheless, the emergence of convergence clubs indicates that countries within each club are becoming more similar, albeit at varying speeds, in terms of per-capita income, financial development, and energy diversification. While there is still considerable progress to be made, the findings suggest that lagging countries are actively leveraging their limited resources and capabilities to catch up with leading nations within their respective clubs.

Second, our study found that while energy diversification positively influences per capita income, the effect is statistically insignificant, different from Hypothesis 2a. This outcome can be attributed to the slow energy consumption growth in OECD countries, averaging just 1.24% annually from 1997 to 2022, compared to 5.93% in non-OECD countries [5]. Furthermore, OECD nations' heavy reliance on fossil fuels, supported by well-established infrastructure, hampers the transition to renewable energy sources, restricting the potential economic benefits of energy diversification.

Third, our study found that financial development positively influences per capita income, supporting Hypothesis 4b and aligning with previous studies such as Aydin and Malcioglu (2016), Madsen and Ang (2016), Purewal and Haini (2022), and Hashemizadeh *et al.* (2023) on OECD countries. This indicates that financial development plays a critical role in driving economic growth in these nations.

Fourth, we found an insignificant effect of per capita income on financial development in OECD countries, which does not support Hypothesis 4a. This may be due to slower economic growth in OECD countries (averaging 2.04% annually) compared to the global average (3.01%) [6]. The robust regulatory frameworks in these countries, while ensuring stability, may also limit financial innovation and the ability to adapt to evolving market needs.

Fifth, our study found that energy diversification positively impacts financial development, supporting Hypothesis 3b. Although energy diversification is slow, it is efficient due to regulatory frameworks promoting SDG 7 (Affordable and Clean Energy). This efficiency has spurred innovation in financial products, such as green bonds and loans, and stabilized energy prices, which are beneficial for economic activities, further boosting financial sector growth.

Sixth, our study identified a positive impact of financial development on energy diversification, supporting Hypothesis 3a and aligning with the findings of Shahbaz *et al.* (2023) on Australia. The advanced financial systems and robust regulatory frameworks in OECD countries promote access to sustainable finance, facilitating a smoother and more efficient transition to renewable energy sources.

Seventh, our study initially found a negative impact of per capita income on energy diversification, supporting Hypothesis 2b and aligning with Shahbaz *et al.* (2023) on Australia. This suggests that fossil fuels remain the preferred choice for economic growth in OECD countries. However, further analysis revealed a U-shaped effect, with the turning point at $67,112.8 per year (constant 2015 USD). At higher income levels, households and corporations become more aware of environmental and energy security issues and have the financial and technological means to diversify their energy mix.

Finally, our study highlights the positive role of technological progress in fostering convergence in per capita income and energy diversification among OECD countries. Technological innovation drives economic growth (Cheng *et al.*, 2021; Khan *et al.*, 2024) and enables more efficient energy generation from diverse sources (Zhang *et al.*, 2024; Zhao *et al.*, 2024), which supports energy diversification. However, technology's limited impact on financial development convergence may stem from the stability-focused financial systems in OECD countries post-financial crises.

5. Conclusions and policy implications

This study examined whether energy diversification, financial development, and per-capita income in OECD countries converged over the period 1997–2021. Using the convergence tests of Phillips and Sul (2007, 2009), we found no evidence of overall convergence for these factors among OECD countries. However, we identified convergence clubs for each factor. We also investigated the determinants of convergence. Using Granger causality tests, we found bi-directional relationships between the three variables in the short run. Long-run panel regression analysis confirmed that technological progress significantly improved per-capita income and energy diversification. It also revealed bi-directional relationships between energy diversification and financial development, an uni-directional relationship from financial development to per-capita income, and a U-shaped effect of per-capita income on energy diversification, with a turning point at $67,112.8 per year. Additionally, fixed capital, labor, and international trade contribute to wealth improvement, while human development and fixed capital contribute to financial system development, and rising oil prices and human development contribute to energy diversification.

The findings of our study provide several important policy implications. While no clear evidence of overall convergence exists among the 38 OECD countries, the formation of convergence clubs for energy diversification, per-capita income, and financial development suggests that lagging countries can catch up with leading ones within their respective groups. By maximizing their resources and capabilities, lagging countries can enhance energy diversification, reducing dependence on fossil fuels and increasing the share of renewable energy. This transition improves energy security, productivity, and accessibility, aligning with

SDG 7 (Affordable and Clean Energy). Additionally, increased renewable energy usage lowers greenhouse gas emissions, contributing to SDG 13 (Climate Action).

The significant role of technological progress in improving per-capita income and energy diversification highlights the need for policymakers in lagging countries to prioritize innovations in energy generation and production. Implementing incentives for technological advancements and sharing best practices in renewable energy adoption and economic strategies can accelerate progress.

The bi-directional relationship between energy diversification and financial development and the uni-directional impact of financial development on per-capita income underscore the importance of robust financial systems. Policymakers should develop sustainable finance mechanisms, such as green bonds, green loans, and carbon credits, by strengthening regulatory frameworks and supporting innovative financial products. Expanding access to affordable financial services can create jobs, boost productivity, and raise living standards, contributing to SDG 8 (Decent Work and Economic Growth).

The U-shaped effect of per-capita income on energy diversification indicates that lower-income OECD countries rely more on fossil fuels, while higher-income nations invest in renewables. Tailored policies are needed to accelerate energy transitions in lower-income countries. Higher-income nations can support this by sharing successful models, transferring clean energy technologies, and providing financial and technical assistance to reduce fossil fuel dependency.

The findings on human and fixed capital suggest that investing in these areas can significantly enhance per-capita income, financial development, and energy diversification, helping lagging countries close the gap with leading ones.

Data availability: Data in support of findings of this study is available from the corresponding author upon reasonable request.

Notes

1. World energy consumption on average grows at 1.91% per year over1980-2022 period using data collected from EIA.
2. Authors' calculation using data collected from EIA.
3. https://wits.worldbank.org/trade_outcomes.html
4. Exponential (2.045/(2*0.092)), where 2.045 and 0.092 are the estimated coefficients of ln(per-capita income) and ln(per-capita income)^2 reported in the second column of Table 7.
5. Authors' calculations using energy consumption data downloaded from EIA.
6. Authors' calculation using GDP growth data downloaded from World Bank.

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Appendix

List of 38 OECD countries

Australia, Austria, Belgium, Canada, Switzerland, Chile, Colombia, Costa Rica, Czechia, Germany, Denmark, Spain, Estonia, Finland, France, United Kingdom, Greece, Hungary, Ireland, Iceland, Israel, Italy, Japan, South Korea, Lithuania, Luxembourg, Latvia, Mexico, Netherlands, Norway, New Zealand, Poland, Portugal, Slovakia, Slovenia, Sweden, Turkiye, United States

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