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Do FinTech trigger renewable energy use? Evidence from OECD countries

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ABSTRACT

This study highlights the importance of financial technologies ("FinTech") as a factor influencing renewable energy use across Organization for Economic Cooperation and Development (OECD) countries. Renewable energy development is motivated notably by reducing carbon dioxide emissions, growing energy security concerns, and oil price volatility. FinTech affects consumption, savings, and investment decisions in the renewable energy sector. Examples include cryptocurrencies such as NRGcoin, blockchain-based renewable energy certificates such as Origin from the Energy Web Foundation, and crowdfunding to raise funds for renewable energy projects. This study aims to quantitatively determine the influence of FinTech development on renewable energy consumption. To this end, it uses a balanced panel of 21 OECD countries for the period 2005–2018. The empirical model is estimated using the fixed-effects estimator with Driscoll-Kraay standard errors. The findings indicate the existence of a significant positive relation between FinTech development and renewable energy use. The results provide a platform for governments and policymakers to promote environmentally sustainable energy sectors by fostering and encouraging the use of FinTech.

1. Introduction

Renewable energy is an alternative to fossil fuels that can substantially reduce carbon dioxide emissions. Nguyen and Kakinaka [1] show that renewable energy consumption is negatively associated with carbon emissions and positively associated with output for high-income countries. Renewable energy includes geothermal, solar, wind, biofuels, and biomass electric power. According to the International Energy Agency [2], renewables have grown rapidly in recent years, encouraged by supportive policies, solar photovoltaics and wind power cost reductions. Renewables represented 26% of global electricity generation in 2018. However, as electricity represents only 20% of global energy consumption, renewables in the transportation and heating sectors will be critical to the energy transition. In addition to the environmental benefits of renewable energy, its development is also notably motivated by growing energy security concerns and oil price volatility.

Yue et al. [3] demonstrate that, on the one hand, financial development can increase energy consumption by (i) facilitating access of consumers to durable goods that consume more energy such as cars, appliances, houses [4], (ii) facilitating cheaper and easier access to financial capital that enables existing and new businesses to grow and expand production which has a direct effect on energy use, (iii) bringing in foreign direct investment, (iv) enhancing consumer and business confidence which results in a rise in economic activity and energy demand [5–8], and (v) boosting stock market activity, hence creating a wealth effect that increases demand for energy-intensive products [4]. On the other hand, financial development may help reduce energy use by encouraging renewable energy and making innovative technologies and energy-saving initiatives more accessible and affordable [9,10]. Furthermore, when foreign investors use technology that is superior to the existing one, foreign direct investment may result in a reduction in energy use [11–13].

According to Levine [72], financial systems (i) produce ex-ante information about possible investments, (ii) monitor investments and implement corporate governance after financing is done, (iii) facilitate the trading, diversification, and management of risk, (iv) mobilize and pool savings, and (v) ease the exchange of goods and

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services. Therefore, financial development occurs when financial instruments, markets, and intermediaries facilitate these five financial functions.

Financial development encompasses the introduction of new financial technologies (also known as FinTech).The Financial Stability Board [14] defines FinTech as “technologically enabled financial innovation that could result in new business models, applications, processes, or products with an associated material effect on financial markets and institutions and the provision of financial services.” The motivation for the emergence of financial technologies is that financial intermediation's unit cost has not changed much over a century [15]. FinTech is the convergence of multiple technologies (e.g., mobile devices, wireless networks, web technologies). FinTech is generally divided into banking, insurance, and regulations [16]. FinTech provides an alternative source of finance for businesses and households, improves access to credit for some underserved segments, and enhances financial intermediation efficiency [17]. An analysis of the global trends in the FinTech industry's development has shown that the volume of investments in this area in 2018 was USD 111.8 billion, almost six times more than in 2013 [18].

Cryptocurrencies such as NRGcoin are an example of FinTech applied to renewable energy use. NRGcoin (NRG) is a blockchain-based cryptocurrency for renewable energy. NRGcoin was established in partnership with Enervalis, a FinTech company based in Belgium founded in 2013. NRGcoin works because when a prosumer produces energy and injects it into the grid, the smart meter at her home generates 1 NRGcoin for every 1 kWh of renewable energy that she injects into the grid. The prosumer can sell her coins on the NRGcoin currency market at any time. On the orther hand, when customers use renewable energy from the grid, their smart meter automatically bills them in NRGcoin rather than conventional currency. Regardless of the actual retail cost of electricity, 1 kWh of renewable energy consumed from the grid costs 1 NRGcoin. The decentralized NRGcoin protocol – a software running on the peer-to-peer network of smart meters – governs all digital transactions involving NRGcoins, including their development. As a result, NRGcoins serve all stakeholders in the smart grid. It acts as a subsidy for renewable energy installations, with prosumers facing a lower risk of policy reform. NRGcoins provide customers with a new payment option as well as lower-cost renewable energy. When renewable energy use is higher, the availability of NRGcoin on the currency exchange market is higher, the price of NRGcoin falls, lowering the cost of renewable energy. Finally, since it is a peer-to-peer currency, NRGcoin can process micro-payments, such as energy payments, every 15 min with almost no overhead costs [19].

Another example of FinTech applied to renewable energy use includes blockchain. Today, a significant challenge facing the renewable energy sector is the traceability or identification of the generating asset power stream. Blockchain-based renewable energy certificates solve this problem [20]. As more individual producers emerge (by installing a small solar photovoltaic plant on their house's roof, a small hydropower plant at a river nearby, …), the energy market becomes more widespread and raises the challenge of traceability. The inability to trace where the power comes from is due to the absence of distinction between electrons from renewable energy sources and electrons from fossil fuels. The Energy Web Foundation (EWF), a not-for-profit FinTech organization created in 2017 and based in Germany, came up with a solution to the energy traceability problem, called Origin.[1] Every generating renewable energy asset linked to the energy web chain is awarded Energy Attribute Certificates—EACs—equal to the amount of generated power. EACs include (i) the source of the power (solar, wind, hydro, etc.), (ii) the geographic location of the generating asset, (iii) the exact amount of electricity generated, and (iv) the date and time. The renewable energy certificates can be traded on a blockchain-based credit market and are therefore more efficient than all other vastly manual-driven projects currently available.

Crowdfunding is another FinTech that has been used to promote the use of renewable energy. Entrepreneurs in the renewable energy sector have turned to crowdfunding platforms such as Kickstarter and Indiegogo to raise funds. The GEN - Produce Renewable Energy for Your Home, which received support from 125 sponsors and surpassed the $60,000 target, is an example of a project that met its objectives. This project aimed to upgrade rooftop energy generation from a traditional solar photovoltaic system to one that included wind, thus raising total capacity and providing energy even when the sun is not shining. Though private investors are a significant funding source for emerging energy technology, the boom in renewable energy ventures on crowdfunding platforms demonstrates their importance.[2]

Hence, FinTech can influence consumption, savings, and investment decisions, and by doing so, they can affect the production and use of renewable energy. This study aims to fill a gap in the energy literature by investigating the impact of FinTech development on OECD countries' renewable energy consumption.[3] In addition to data availability, the focus on OECD countries was motivated by their large share of FinTech startups and renewable energy use in the world. According to the Crunchbase database, FinTech startups in OECD countries represented 60.92% of the total number of FinTech startups globally in 2018. Renewable energy consumption in OECD countries represented 57.9% of renewable energy consumption in the world.[4]

This study uses the fixed-effects panel regression estimator with Driscoll-Kraay standard errors to estimate the proposed model's main Hypothesis. Driscoll-Kraay standard errors are heteroskedasticity and autocorrelation consistent and robust to general forms of cross-sectional and temporal dependence. This study contributes to the existing body of knowledge across several dimensions. Firstly, it increases awareness and comprehension about the role of FinTech development in fostering the adoption of renewable energy solutions. Secondly, to the best of the authors' knowledge, it is the first to quantitatively assess and examine FinTech development's influence on renewable energy consumption across OECD countries. Thirdly, it attempts to measure the level of FinTech development in OECD countries by constructing a proxy indicator. Fourthly, the findings of this study establish, while controlling for other economic development indicators and control variables, FinTech development as a significant factor influencing renewable energy consumption. Therefore, this study's findings give governments and policymakers valuable insights and have important policy implications as they show that promoting FinTech development in OECD countries encourages renewable energy use.

This paper is structured as follows. Section 2 provides a review of the literature. Section 3 describes the data and the methodology

[1] Energy Web. (n.d.). *Tomorrow's Renewable Energy Markets Start Here*. Retrieved April 14, 2021, from https://energyweb.org/technology/toolkits/ew-origin/#:~:text=EW%20Origin%20is%20a%20suite,and%20net%2Dzero%20carbon%20targets.

[2] Smart Energy International. (2018, October 13). *Crowdfunding in the Energy Transition.* https://www.smart-energy.com/industry-sectors/policy-regulation/crowdfunding-in-the-energy-transition/.

[3] OECD countries account for 80% of world trade and investment.

[4] BP. (n.d.). *Statistical Review of World Energy*. Retrieved April 14, 2021, from https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html.

adopted. Section 4 presents and interprets the results. Section 5 concludes.

2. Literature review

This paper builds on two closely related strands of the academic literature. The first one studies the nexus between financial development and energy use. The second explores the nexus between financial development and renewable energy consumption.

2.1. The nexus between financial development and energy use

The channels by which financial development can affect energy use are summarized in Table 1.

The first strand of academic research on the relation between financial development and energy consumption suggests an overall positive effect. When both private and domestic credit proxy financial development, Chang [22] shows that energy use rises with income in emerging and developing economies. Energy use also rises with financial development in poor countries. Sadorsky [5] shows, when stock market ratios proxy financial development, a positive and statistically significant relationship between financial development and energy consumption in 22 emerging countries for 1990–2006. Sadorsky [6] shows that the growth of the banking industry has a significant positive influence on energy use in central and eastern European countries for 1990–2006. Coban and Topcu [21] show that financial development is positively associated with a rise in energy use in old EU member countries. Its effect on energy use in new EU member countries depends on the proxy used for financial development. No significant impact was found when financial development was proxied by stock index variables. Islam et al. [23] show a significant positive association between financial development and energy use in Malaysia. Ozturk and Acaravci [24] found that financial development and energy use are significantly and positively associated in Turkey between 1960 and 2007. Mukhtarov et al. [25] established a positive and statistically significant association between financial development, GDP growth and energy consumption in Kazakhstan between 1993 and 2014.

Other studies instead indicate an overall negative effect of financial development on energy consumption. Chang [22] finds that energy use slightly declines with financial development in advanced economies when values of traded stocks and stock market turnover proxy financial development. Shahbaz et al. [26] use an autoregressive distributive lag (ARDL) model and study the relationship between globalization and energy consumption in India between 1971 and 2012 while accounting for financial development, urbanization, and economic growth. Their results show that financial development is negatively and significantly associated with energy use. Topcu and Payne [27] use panel data for 32 rich countries between 1990 and 2014 and establish that a rise in the stock market index leads to a slight decrease in energy use. Destek [4] studies 17 emerging economies between 1991 and 2015 and found that banking and bond market development have a negative and statistically significant effect on energy use. Bond market development has the most substantial impact on energy consumption reduction. Ouyang and Li [28] study China between 1996 and 2015 and found that financial development (measured by an index resulting from a principal component analysis) is negatively associated with energy use.

Furthermore, some studies find a two-way causality between financial development and energy use. Islam et al. [23] investigate causal relationships using a Vector Error Correction Model (VECM) in Malaysia between 1971 and 2009. They find two-way causality between financial development and energy use. Furuoka [29] shows a long-run equilibrium relationship between finance and energy use in Asia between 1980 and 2012.

Finally, some authors find no significant association between financial development and energy consumption. When using the overall financial development index, Topcu and Payne [27] find an absence of significant association between financial development and energy use. Shahbaz et al. [30] show no significant causality between India's financial development and energy use between 1960 and 2015.

These heterogeneous results are explained by using different financial development indicators, diverse methodologies, and studying various periods and geographical areas. They are also due to several other non-financial factors such as resource availability, geographical regions, or the countries' socio-political context.

2.2. The nexus between financial development and renewable energy use

There are fewer papers that explore the relation between financial development and renewable energy consumption.

Some find no significant impact of financial development on renewable energy use. Burakov and Freidin [31] find no causality running from financial development to renewable energy consumption in Russia from 1990 to 2014. Assi et al. [32] examine the influence of financial development, environmental pollution, innovation, economic freedom, and real Gross Domestic Product (GDP) per capita on renewable energy use in the ASEAN + 3 economies between 1998 and 2018. Their research concludes that financial growth does not affect renewable energy use.

However, the vast majority of the literature finds a positive impact of financial development on renewable energy consumption. Wu and Broadstock [33] use data from 22 emerging markets countries' from 1990 to 2010 and find a significant positive association between financial development and renewable energy use. Best [34] studies 137 countries for 1998–2013 and finds that credit from banks and domestic private debt securities positively influence renewable energy use in high-income countries. Kutan et al. [35] explore the role of foreign direct investment and stock market development on promoting renewable energy consumption across a panel of Brazil, China, India, and South Africa from 1990 to 2012. The results show that foreign direct investment and stock market development foster renewable energy consumption. Shahbaz et al. [26] use annual data from India for 1971–2012 to study the relation

Table 1
Effect channels of financial development over energy consumption.

Effect channels	Description
Direct effect	Consumers' access to durable goods that increase energy use is made easier by the growth of the financial sector.
Business effect	Financial development allows for the growth and development of new businesses and increases production, directly affecting energy demand.
Wealth effect	Financial development can increase confidence and boost economic activity that promotes energy demand.
Substitution Effect[a]	Financial development provides easier access to innovative technology and energy-saving projects that may decrease energy demand.

Sources [6,21].
[a] The substitution effect is added to the effects identified in Sadorsky [6] and Coban and Topcu [21].

between globalization and energy use controlling for economic growth, financial development, and urbanization. The findings reveal that financial development promotes renewable energy sources. Raza et al. [36] examine the nonlinear association between financial development and renewable energy consumption in fifteen top renewable energy consumption countries for 1997–2017 and find that financial development increases renewable energy consumption. Anton and Nucu [37] explore the impacts of financial development on renewable energy consumption for 28 EU countries from 1990 to 2015, finding that financial development positively influenced the use of renewable energy. Khan et al. [38] examine the heterogeneity of renewable energy consumption, carbon dioxide emission, and financial development for a global panel of 192 countries. The study uses panel quantile regression to tackle distributional and unobserved individual heterogeneity. Results indicate that financial development positively affects renewable energy consumption. Wang et al. [39] investigate the relation between renewable energy use, economic growth, and financial development in China. The study examines the long-run and short-run effects of economic growth and financial development on renewable energy use in China using panel data from 1997 to 2017. The long-run relationships indicate that economic growth stimulates renewable energy use, whereas financial development has a detrimental effect. However, the short-run relationships indicate that economic growth and financial development have a negative and positive effect on renewable energy usage, respectively. Additionally, the authors use the Granger causality test to determine the existence and direction of causal relationships between variables. The findings of the causality test indicate a unidirectional causal relationship between financial development and renewable energy consumption. Alsagr and van Hemmen [40] examine the effect of financial development and geopolitical risk on renewable energy use in developing countries from 1996 to 2015. Using a two-step Generalized Method of Moments (GMM), they find that financial development significantly and positively impacts the transition to renewable energy. Based on these findings, the level of financial development is used as a control variable in this paper.

3. Methodology

3.1. Theoretical framework and control variables

To derive testable conjectures regarding the relationship between FinTech formation and renewable energy use, this study considers the need for renewable energy to mobilize finance and how FinTech can assist with this mobilization. As Sonntag-O'Brien and Usher [41] highlighted, renewable energy is a multi-billion-dollar industry but remains a small segment of the world's energy industry. In fact, in 2019, the share of renewables in the total OECD primary energy supply represented 10.8% [42]. Various finance-related risks and barriers are hindering faster growth. Renewable energy sites are competing on cost with conventional fossil fuel energy sources. Most renewable energy projects have relatively low rates of return and high up-front capital costs relative to competing technologies. Many investors are only willing to invest under unfavorable terms for the project developer. For instance, in 2019, investors in major renewable energy sources were reported to look for FinTech tools and platforms enhancing their understanding of their assets' operating and financial performance.[5] Their goal was to optimize their return profile in an increasingly competitive marketplace. Sonntag O'Brien and Usher [41] advocate that the financing of a renewable plant is different from conventional financing; it requires new thinking and new forms of capital. Besides, they posit that energy markets are not perfect and that due to insufficient information in these markets, project risk tends to be overestimated, and transaction costs can rise. In 2020, as fund managers look to stabilize portfolios, the use of data for performance validation proves crucial to establishing renewable energy as an infrastructure investment of choice.[6]

The FinTech industry has been found to provide new capital forms (for instance, through digital lending [43]). It can also provide new risk management approaches. In fact, with emerging technologies, such as cloud, analytics, and big data, the FinTech industry can provide insights on the likelihood, severity, and timely detection of risks. FinTech companies facilitate the obtention and circulation of information [15] and, by doing so, ease risk assessment and management and lower the external financing costs. This is an illustration of what was previously referred to as a business effect. A question arises as to whether these benefits apply to the renewable energy sector. If they do, the higher the number of FinTech startups, the easier the mobilization of finance for renewable energy projects, and the higher the supply of renewable energy. The development of FinTech may also give rise to direct and wealth effects that may positively impact renewable energy demand. If this is the case, this study posits that the higher the number of FinTech startups, the higher the use of renewable energy due to increases in supply and demand. The primary purpose of this paper is, therefore, to test this conjecture. It also aims to quantify the relation between FinTech development and renewable energy use. Hence, the following main Hypothesis will be tested:

Hypothesis. FinTech development positively influences renewable energy consumption.

Furthermore, this study controls for variables established in the energy literature to impact renewable energy use. Hence, the use of renewable energy is expected to be affected by each country's wealth level and growth for each year [5,44]. Sadorsky [44], using panel estimates, shows that increases in real per capita income positively and statistically significantly impact per capita renewable energy consumption. The positive relationship is confirmed in Sadorsky [5], who finds that the estimated coefficient on the income variable (real GDP per capita) is positive and statistically significant. Energy prices are also established to influence the use of renewable energy, and based on previous findings, a positive effect is expected [33,37,45]. As is common in the energy literature, this study uses the consumer price index to proxy energy prices [22,37,46]. The proposed model also considers that the use of renewable energy may be impacted by foreign direct investment and, based on the existing literature, a positive effect is expected [47–49]. Finally, as previously mentioned, renewable energy use is affected by the level of financial development [33–35].

3.2. Construction of FinTech indicator

This study follows Haddad and Hornuf [50] and constructs an indicator for FinTech new startup formations per country. This indicator explores the formation of FinTech startups in general without concentrating on one specific type of FinTech business model. This study uses the CrunchBase database, a crowdsourced

[5] Techcrunch. (2019, May 30). *Fintech and cleantech … an odd couple or a perfect marriage?* Retrieved from https://techcrunch.com/2019/05/30/fintech-and-clean-tech-an-odd-couple-or-a-perfect-marriage/?guccounter=1.

[6] Fintech News. (2020, June 24). *Data to play a key role in unlocking renewable energy investment post-pandemic – CLIR*. Retrieved from https://www.fintechnews.org/data-to-play-key-role-in-unlocking-renewable-energy-investment-post-pandemic-clir/.

resource for finding companies and investors and getting detailed information on new FinTech startup formations. Furthermore, the database includes profiles for more than 60 000 investors and 300 000 private enterprises [51]. This database had been previously used in several studies [50,52,53]. A retrieving mechanism based on keyword searches identified a total of 14530 FinTech startups for the sample of 21 OECD countries used in this study for the period between 2005 and 2018. In line with previous industry studies and reports [50,54,55], the sample collected included data related to nine FinTech categories: financing, insurance, banking, real estate, asset management, financial exchanges, risk management, loyalty programs, and payments. The information obtained was organized to construct a balanced panel dataset that shows the number of new FinTech startups per country and per year (FINT) for each of the 21 OECD countries over 2005–2018. Table A1 in the Appendix presents the list of countries included in the sample. It shows the number of FinTech started in 2018 and the average annual number of FinTech startups per country for the period of the study.

3.3. Data used

To explore the impact of FinTech startup formations on renewable energy consumption, this work uses a balanced panel dataset for 21 OECD economies for the years 2005–2018. The study period and the countries included in the sample were chosen based on the data available for all the annual time series used in the empirical analysis. Data for Renewable Energy Consumption (RENC) measure the consumption of renewable energy expressed in Millions of tons of oil equivalent (Mtoe). Income is evaluated by the Gross Domestic Product Per Capita (GDPPC) expressed in constant 2010 US$. Gross Domestic Product per Capita Growth (GDPCG) is calculated as the annual percentage growth of GDP per capita based on constant local currency. Foreign Direct Investment (FDI) measures the net inflows of investment to obtain a lasting management interest (10% or more of voting stock) in a firm performing operations in a country different than that of the investor. It shows net inflows as a percentage of GDP. Besides, since energy price data is not available for all the 21 countries included in the sample and for all years, the Consumer Price Index (CPI) is utilized to proxy energy prices following previous studies within the energy literature [5,22,37,56,57]. CPI measures the fluctuations in the price of a typical basket of consumer goods and services. Finally, the Financial Institution Depth index (FID) is used to proxy the general financial sector development level. Previous studies used domestic credit by the banking sector as a share of GDP as an indicator for the financial development level [9,58]; however, this study adopts the FID index. The FID index compiles data on bank credit to the private sector as a percentage of GDP, pension fund and mutual fund assets to GDP, and insurance premiums (life and no-life) as a per cent of GDP. This index's values are normalized and range between 0 and 1, where lower values reveal a lower level of financial development in terms of financial institutions' depth. Various sources were used to retrieve the data: World Bank Development Indicators (WDI) database (GDPPC, GDPCG, FDI, CPI), BP statistical review of world energy main indicators and world bank sustainable energy for All (SE4All) database (RENC) and International Monetary Fund data (FID index). The logarithmic transformations for the RENC (LRENC) and GDPPC (LGDPPC) were performed to allow comparability across the different explanatory variables.

Table 2 indicates the descriptive statistics for the balanced panel with 21 countries for the period 2005–2018. The standard deviation for the RENC variable is 18.34, which reveals that the sample is diverse regarding renewable energy consumption. The United States presented the highest level of renewable energy consumption of 131.46 Mtoe for 2018, while the lowest level for renewable energy consumption is observed in Israel for 2007. In fact, the US renewable energy consumption attained a record level of 11.5 quadrillions Btu in 2018, rising by 3% compared to 2017. This increase is mainly due to wind and solar power plants [42]. The use of renewables in the US played a substantial role in the economy during the last decade. The US is considered a global leader in new renewable technologies [59]. Additionally, Table A2 in the Appendix shows the average renewable energy consumption in Mtoe for the 21 OECD countries for the period 2005–2018. The results presented in Table A2 confirm that the US has, on average, the highest level of RENC for the period 2005–2018 and that Israel has the lowest level.

Table 2
Descriptive statistics for variables used in the empirical analysis.

Variable	Mean	Std. Dev.	Minimum	Maximum
RENC (Mtoe)	9.36	18.34	0.01	131.46
LRENC	1.12	1.59	−4.57	4.88
FINT	49.42	124.61	0	778
LGDPPC	10.51	.54	9.10	11.288
CPI	103.13	11.94	65.85	203.54
FDI	5.13	10.35	−26.19	86.59
FID	.70	.24	.11	1
GDPCG	1.44	2.79	−8.51	23.98

Regarding the new FinTech startups formation indicator, the United States (US) scored the highest average number of FinTech startups, as shown in Table A1 in the Appendix, while Belgium and Finland have the lowest average of 6 new FinTech startups per year. These results align with Haddad and Hornuf [50], who also find that the US has the largest market share of new FinTech startup formations.

Table 2 displays the descriptive statistics for the balanced panel with 21 economies for the period 2005–2018. RENC refers to Renewable Energy Consumption expressed in Millions of tons of oil equivalent (Mtoe). LRENC and LGDPPC represent the natural Logarithms of Renewable Energy Consumption and Gross Domestic Product Per Capita. CPI denotes the Consumer price index. FDI and FID indicate the Foreign Direct Investment and Financial Institution Depth index. GDPCG shows the Gross Domestic Product per Capita Growth.

Table 3 shows the correlation matrix between the independent or endogenous variable of interest represented by the LRENC and the explanatory or exogenous factors used in this study (FINT, LGDPPC, CPI, FDI, GDPCG) as well as the correlations between the various explanatory variables. RENC shows a relatively high level of positive correlation with the FinTech development indicator. In addition, a positive correlation is observed between the financial development indicator proxied by the FID index. Furthermore, the correlation matrix presented in Table 2 indicates that a positive correlation exists between RENC and both GDPPC and prices proxied by the CPI, while the FDI is negatively correlated with

Table 3
Correlation matrix.

Variable	LRENC	FINT	LGDPPCC	CPI	FDI	FID	GDPCG
LRENC	1.000						
FINT	0.494	1.000					
LGDPPC	0.190	0.167	1.000				
CPI	0.328	0.090	−0.099	1.000			
FDI	−0.177	−0.073	0.176	−0.090	1.000		
FID	0.151	0.194	0.873	−0.128	0.152	1.000	
GDPCG	−0.150	−0.039	−0.164	0.008	0.257	−0.162	1.000

RENC. Therefore, these results suggest that RENC can be assumed to be a function of FINT, LGDPPC, CPI, FDI, FID, GDPG, which are shown to be correlated with correlation coefficients varying from 0.152 to 0.494.

3.4. Estimation technique

This research investigates the influence of FinTech development on renewable energy consumption. To this end, a balanced panel of 21 OECD countries for the period 2005–2018 is used. The model presented in equation (1) is considered a general representation to explore the impact of FinTech development on renewable energy use while accounting for the influence of three main control variables: LGDPPC, CPI, and FDI. The use of panel data represents several benefits as it offers greater flexibility when trying to model behavioral differences across the various units [60]. It also provides different advantages as it ensures higher variability, less collinearity between the various factors, as well as granting higher degrees of freedom and better efficiency [60].

The first step of the empirical analysis is to check for possible multicollinearity. To this end, the Variance Inflation Factors (VIF) for all the variables were calculated. The results show that the VIF for all the variables used in this study were below the threshold value of 5, indicating that multicollinearity is not an issue [61]. Furthermore, the Jochmans portmanteau test for within-group correlation in panel data is performed to test for serial correlation [62]. The test is appropriate for short panels and accounts for heteroskedasticity. The portmanteau test results confirm that serial correlation is not present in the errors.

The econometric approach to estimate panel data with a relatively small size (21 cross-sectional units and 14 time periods) relies on two techniques, fixed and random-effects [60]. The individual effects and the exogenous variables are not correlated for the random-effects estimator. Further, they are randomly spread between the various units to capture the individual effects. The intercept term is, therefore, constant across all the cross-sectional units. However, under the fixed-effect estimator, each unit has its own individual effect that is interrelated with the predictor variables [63]. The fixed-effect estimator is adopted to explore the influence of variables that change across time. Within this model, the intercept term will represent the fixed country effect. With relatively small samples, the fixed-effects model is considered better suited for estimating the parameters [64]. Moreover, the fixed effects model is considered suitable if the empirical analysis focuses on a specific set of countries like a set of N OECD countries [60].

In addition, the fixed-effects model allows minimizing the risks associated with possible omitted variables biases related to time-invariant cross-sectional unit characteristics by accounting for country individual fixed-effects [65]. These unobserved time-invariant individual effects can account for possible omitted variables such as historical, political, or institutional factors for countries. This study mainly focuses on the impacts of FinTech development rather than exploring cointegration relations or bidirectional causality between the variables. Therefore, the fixed-effects estimator is appropriate as it does not entail testing for the variables' non stationarity and integration, which is a required precondition to conduct the cointegration analysis. Previous empirical works have shown that the order of integration for energy and financial variables could be either I(0) and I(1), which does not allow to apply a cointegration analysis where all the variables are required to have unit root [37].

The Hausman test is used to examine if the fixed-effects estimator is the appropriate technique [66]. The test results for the model misspecification show that the fixed-effects estimator is the proper one to adopt. The p-values for the test for the main model and the augmented one are both less than 0.05 (H = 12.29 with p-value = 0.0153 for the main model, and H = 42.82 with p-value = 0.0000 for the augmented model); hence, the fixed-effects estimator should be adopted. The equations below describe the fixed-effects models for the basic and augmented models:

$$LRENC_{it} = \beta_0 + \beta_1 FINT_{it} + \beta_2 LGDPPC_{it} + \beta_3 CPI_{it} + \beta_4 FDI_{it} + \nu_i + \varepsilon_{it} \quad (1)$$

$$LRENC_{it} = \beta_0 + \beta_1 FINT_{it} + \beta_2 LGDPPC_{it} + \beta_3 CPI_{it} + \beta_4 FDI_{it} + \beta_5 FID_{it} + \beta_6 GDPCG_{it} + \nu_i + \varepsilon_{it} \quad (2)$$

where, L indicates the natural logarithm; $i = 1 \ldots, N$ indicates the subscript for each unit, and $t = 1 \ldots, T$ refers to the time period, ν_i represents the country-specific effect, this effect is time-invariant, and it accounts for any unknown unobservable individual country-specific effect that is not included in the proposed model and ε_{it} is the random error term. To get tractable models and make the explanations of the results more straightforward, this study performs the logarithmic transformation for the RENC variable and the GDPPC.

One of the limitations of using panel data is the possible presence of heteroscedasticity or cross-sectional dependence or both. This can generate incorrect inferences. This work uses the Pesaran CD test to investigate any possible cross-sectional dependence in the model's variables [67]. Moreover, the Wald test for groupwise heteroscedasticity in the residuals of a fixed effect estimator is performed [68]. The Pesaran CD test results reveal the presence of cross-sectional dependence for the basic and augmented models (CD test statistic = 9.844, Pr = 0.000 for the basic model and CD test statistic = 7.573, Pr = 0.0000 for the augmented model). Finally, the results of the Wald test reject the null of homoscedasticity (chi2 test statistic = 10475.56, Prob = 0.000 for the basic model and chi2 test statistic = 21731.37, Prob = 0.000 for the augmented model). Therefore, the fixed-effects model with Driscoll-Kraay standard errors is used to assess the influence of FinTech development on renewable energy use. The Driscoll-Kraay standard errors are "heteroskedasticity-and autocorrelation-consistent and are robust to general forms of cross-sectional and temporal dependence" [67].

4. Empirical results and discussion

The results for the estimation of the fixed-effects (FE) model presented in equation (1) are reported in Table 4. Overall, the R-squared value of 72.32% shows that the model in equation (1) highly fits the data and explains above 70% of the variation in renewable energy consumption. The findings indicate that FinTech development exerts a positively significant impact on renewable energy consumption at the 5% significance level (β1 = 0.0019, p = 0.0028). This result confirms the proposed conjecture on the relation between FinTech development and renewable energy. A

Table 4
Empirical Results. Fixed effects with Driscoll-Kraay standard errors. Regression using 294 observations, 21 cross-sectional units and 14 time periods. Dependent variable: LRENC.

	Coefficient	Drisc/Kraay Std. Error	t-ratio	5p-value
const	−38.5737	6.4352	−5.9942	0.0000
FINT	0.0019	0.0006	3.4017	0.0028
LGDPPC	3.4438	0.6334	5.4367	0.0000
CPI	0.0339	0.0073	4.6359	0.0002
FDI	−0.0041	0.0008	−4.8991	0.0001

one unit increase in FinTech is linked to a 0.1901% rise in renewable energy consumption, indicating that FinTech development positively influences renewable energy consumption. Hence, the main Hypothesis is validated. These findings are somewhat consistent with the strand of literature that establishes a positive influence of financial development on renewable energy use [33–35,37–40,49]. This study's findings push these results further by showing that FinTech development and innovations in particular, which characterize a well-developed technological financial system, can be considered a significant component that increases renewable energy consumption. These results help fill a gap in the literature tackling renewable energy consumption and financial development and add to it by quantitatively assessing the impact of FinTech development on renewable energy consumption and establishing its role as a significant factor influencing renewable energy use.

Concerning the control variables, the estimation results for equation (1) presented in Table 4 suggest a positive and statistically significant relation between economic development and renewable energy consumption ($\beta2 = 3.4438$, $p = 0.0000$). A 1% increase in GDPPC yields a 3.4861% rise in renewable energy consumption. The study findings support the conservation hypothesis, which indicates that a unidirectional causal relationship runs from economic growth to energy consumption [4,69,70] and are in line with Sadorsky [5,44], who shows that per-capita income exerts a statistically positive impact on renewable energy consumption. Therefore, a slight increase in GDPPC generates a significant direct increase in renewable energy consumption for OECD countries included in this study that are mostly characterized as being developed and high-income countries.

As for the energy prices proxied by CPI, the results show that prices have a positive and significant influence on renewable energy consumption ($\beta3 = 0.0339$, $p = 0.0002$). If CPI increases by one unit, renewable energy consumption increases by 3.4462%. These findings are consistent with previous works that establish a positive relation between energy and renewable energy consumption [33,37,45]. Therefore, higher energy prices contribute to an increase in renewable energy use.

Foreign direct investment exerts a negative and significant impact on renewable energy consumption ($\beta4 = -0.0041$, $p = 0.0001$). If FDI increases by one unit, renewable energy consumption decreases by 0.4108%. However, although the empirical literature establishes a positive relation between energy consumption and FDI, there is no agreement in explaining the association between FDI and renewable energy consumption [49]. Only a few studies tackle the FDI renewable energy consumption nexus. This study's result showing the negative association between FDI and renewable energy consumption matches the results of Anton and Nucu [37], who establish that FDI decreases renewable energy consumption but contradicts the strand of literature that shows a positive association between the two variables [47–49]. One possible explanation could be that FDI might generate large-scale corporate investments and could largely drive technological and digital innovations, which eventually reduce energy consumption.

Table 5
Robustness Check-Augmented Model Empirical Results. Fixed effects with Driscoll-Kraay standard errors. Regression using 294 observations, 21 cross-sectional units and 14 time periods. Dependent variable: LRENC.

	Coefficient	Drisc/Kraay Std. Error	t-ratio	p-value
const	−47.2345	6.9882	−6.7592	0.0000
FINT	0.0021	0.0005	3.9462	0.0008
LGDPPC	4.1671	0.6916	6.0252	0.0000
CPI	0.0281	0.0088	3.2058	0.0044
FDI	−0.0019	0.0021	−0.9097	0.3738
FID	2.3777	0.8946	2.6579	0.0151
GDPCG	−0.0183	0.0115	−1.5887	0.1278

Finally, the robustness of this study results has been tested by adding two exogenous variables to equation (1), Gross domestic product growth and the financial institutions' depth index. The results for this augmented model presented in equation (2) are reported in Table 5. Overall, the R-squared value of 74.78% shows that the model in equation (2) highly fits the data and explains above 70% of the variation in renewable energy consumption. The results confirm the previous findings, which indicate that renewable energy consumption increases with FinTech development ($\beta1 = 0.0021$, $p = 0.0018$). For a one unit increase in FinTech, we expect to see about a 0.2102% rise in renewable energy consumption. The financial development indicator is positive and statistically significant ($\beta5 = 2.3777$, $p = 0.0151$), which matches the findings of the previous works that establish the positive influence of financial development on renewable energy consumption. If FID increases by one unit, renewable energy consumption increases by 9.7801%. Furthermore, the economic growth coefficient appears not to have a statistically significant influence on renewable energy use ($\beta6 = -0.0183$, $p = 0.1278$), which confirms previous results of Anton and Nucu [37] and Acheampong [71], who show that economic growth does not have a causal effect on energy consumption.

5. Conclusion

This study's main objective is to explore the impact of FinTech development on renewable energy consumption across OECD countries for the period 2005–2018. To this end, a balanced panel of 21 OECD economies is used. It constructs a proxy indicator for the level of FinTech development based on data collected from the CrunchBase database. The indicator shows the number of new FinTech startups per country and per year for each of the 21 OECD countries over 2005–2018. Moreover, secondary data for renewable energy consumption, gross domestic product per capita, foreign direct investment, energy prices, financial institutions depth index, and gross domestic product per capita growth were collected for the period of study and countries included in the sample. The model that assesses the effect of FinTech development on renewable energy consumption was estimated using the fixed-effects model with Driscoll-Kraay standard errors. These errors are "heteroskedasticity- and autocorrelation-consistent and are robust to general forms of cross-sectional and temporal dependence" [67]. The findings indicate the existence of a significant positive relation between FinTech development and renewable energy consumption. The results establish FinTech development as a solution to boost renewable energy use in the energy mix.

Furthermore, this study's results offer several relevant implications for policymakers who should consider the new technologies used and applied in the financial services sector when formulating energy policy. The FinTech industry provides new ways to incentivize the production and use of renewable energy, new tools to manage complex power grids made of small heterogenous prosumers, new funding opportunities, new risk management tools. The FinTech industry also facilitates the obtention and circulation of information. These combined benefits are shown to foster the development of the renewable energy sector.

This study is not without some limitations. First, the results are based on data collected from OECD countries. This decreases the chances of generalizing the inferences obtained to different geographical regions; therefore, it is suggested to repeat this empirical exercise in different regions to explore the impact of

FinTech on renewable energy consumption under different structural and economic contexts. Second, due to data availability, this study uses a limited number of variables that are shown to influence renewable energy consumption. Moreover, it constructs a proxy indicator for the level of FinTech development. Future studies may account for different explanatory variables that affect renewable energy consumption and use a real secondary dataset that measures FinTech development as soon as this data becomes available for more extended time frames. Even though this study might suffer from these limitations, the results are considered reliable and statistically significant. Moreover, they open the door for a new line of research that explores the FinTech - renewable energy consumption nexus.

CRediT authorship contribution statement

Alexandre Croutzet: Conceptualization, Writing – original draft, Writing – review & editing, Data curation, Validation, Investigation, Resources, Supervision, Project administration, Funding acquisition. **Amal Dabbous:** Conceptualization, Writing – original draft, Writing – review & editing, Data curation, Methodology, Software, Formal analysis, Validation, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

Table A1
List of Countries, Number of FinTech Started in 2018 and Average Number of FinTech Started Each Year Between 2005 and 2018.

Country	No. FinTech Started in 2018	Average Number of FinTech Started 2005–2018
United States	567	552.93
United Kingdom	151	139.14
Canada	67	53.00
Germany	37	34.86
Australia	24	32.57
France	28	32.43
Spain	29	24.86
Switzerland	35	23.00
Netherlands	15	21.14
Israel	42	20.79
Japan	20	17.00
Ireland	10	11.64
Mexico	10	10.36
Italy	9	10.14
Sweden	5	9.43
Denmark	5	8.36
Korea, Rep,	12	8.29
Turkey	14	7.79
Poland	2	7.14
Finland	11	6.64
Belgium	5	6.36

Table A2
Average renewable energy consumption expressed in Millions of tons of oil equivalent (Mtoe) for the 21 OECD countries for the period 2005–2018.

Country	Mean of RENC 2005–2018
US	77.8963
Germany	28.4451
Spain	13.022
UK	10.6047
Japan	10.194
Italy	10.0264
France	7.21154
Canada	6.74885
Sweden	4.85001
Australia	4.27893
Denmark	3.35456
Poland	3.13776
Netherlands	2.93843
Finland	2.9209
Mexico	2.82534
Turkey	2.39939
Belgium	2.21424
Korea	1.84159
Ireland	1.10182
Switzerland	0.49575
Israel	0.14558

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