Scaling Up the Clean Energy Transition in Turkey: The Role of Financial Development, Green Technologies, and Economic Complexity

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The transition to a low-carbon economy represents a significant challenge and opportunity for Turkey, whose energy mix is 90% fossil fuel. In this context, this research aims to analyse the role of financial development (FD), economic complexity (EC), and environmental technology (PET) on renewable energy consumption (REC) in Turkey over the period from 1980 to 2020. The Fourier Bootstrap ARDL (FBARDL) approach, a new technique that can capture up to five smooth structural breaks and address small sample biases, indicates that a significant 'green structural lock-in' exists, where a 1% rise in FD and EC causes a 1.12% and 0.70% decrease in REC, respectively. In other words, Turkey's financial development and economic complexity are still locked into fossil fuel consumption. In contrast, PET positively influences REC, where a 1% rise in PET causes a 0.12% rise in REC. The Granger causality test further confirms that FD and PET have a one-way causality to REC. The research contributes to the existing literature on the Turkish energy equilibrium, providing a much-needed antidote to the prevailing 'positive finance' assumptions in non-OECD economies.

Keywords: financial development, renewable energy, environmental technology, Turkey, Fourier Bootstrap ARDL
JEL *Classifications:* C22, G20, Q42, Q43

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Introduction

The international need to reduce global warming has brought about a change in global strategy to include the management associated with a global energy transition. The seventh development goal brings about change to ensure a sustainable future (United Nations 2021), which aims to provide clean, sustainable, and affordable energy to everyone world-

wide. Since climate change progress depends on this goal, a total transition to a zero-emission power source needs to take place in a few decades, as stated by International Renewable Energy Agency (2021).

The implications of this transition are especially complex in the context of the emerging economies. Turkey is an especially interesting case to examine in this regard. It is a rapidly growing country and thus a significant consumer of energy. Its energy usage escalated by a massive 55% between the years 2000 and 2019. Nevertheless, Turkey is also a country that is still substantially locked into carbon-rich energy sources. It has a total energy structure in which fossil fuels comprise a massive 91%. The world is seeing record-high expenditure on renewable energy sources, but Turkey's future in this regard seems to be on the wrong trajectory (International Energy Agency 2021; International Renewable Energy Agency 2021).

The relevance of the study is determined by the identification of the exact drivers and inhibiting factors for reversing the trend. Although current literature tends to study the inhibiting factors separately, this paper will offer a 360-degree view of the intersections of the financial systems, environment innovations, and the complexity of the structure of the economy, which impacts the use of clean sources of energy. This study will have significant value since it will reveal the reasons for the inhibiting effects of the financial sector and the structure of the industry of Turkey on the use of renewable sources of energy.

Many emerging economies, including Turkey, have set their sights on adopting strategic policies to boost sustainable energy growth. These efforts are aimed at achieving the target set during COP26 (26th meeting of the Conference of Parties), which emphasizes the importance of energy transition in mitigating the effects of climate change. Turkey is a rapidly developing country with a growing demand for energy. As the country looks towards a more sustainable energy future, financial development and environmental technologies are crucial factors that can facilitate a transition towards cleaner and renewable energy sources.

As shown in figure 1, the Turkey's renewable energy sources case is demonstrating a rather worrying trend with a downward trajectory, especially in terms of the total final energy consumption structure. From this graphical representation of the data, the core issue with our case study is made clear: the energy structure of the country still strongly depends on fossil fuel sources. This constitutes the empirical foundation for our hypothesis that there is a 'green structural lock-in' in Turkey since its

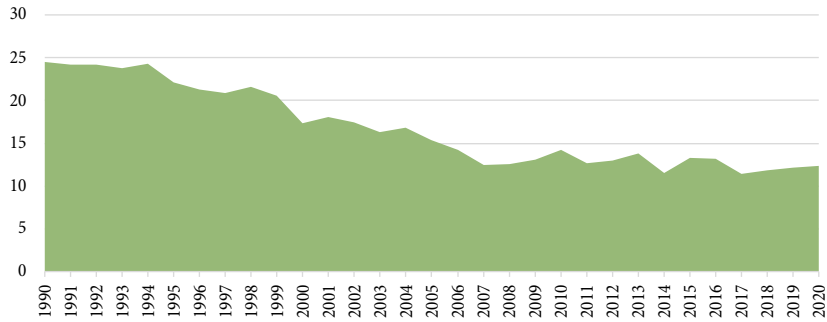


FIGURE 1 Renewable Energy Consumption of Turkey from 1990 to 2020 (based on data from The World Bank (https://databank.worldbank.org/source/world-development-indicators))

industrialization and financial growth are still failing to deliver its positive impacts in terms of its energy structure.

Thus, examining factors that trigger the clean energy transition is imperative. However, this transition cannot be achieved in the absence of the financial sector because according to United Nations Environment Programme (2011), to meet the global transition to a low-carbon economy, it has to be funded by the private sector. Similarly, research indicates that finance can facilitate the deployment of renewable energy technologies and accelerate the transition to sustainable energy sources in Turkey (Mukhtarov et al. 2022). Mukhtarov et al. (2022) also found that financial development plays a pivotal part in the adoption of clean energy sources in Turkey. Furthermore, global investment in renewable energy reached a record high of $305 billion in 2020, representing a 2% increase from the previous year. This increase was attributed to sustainable policies and frameworks, improved technology, decline in financing costs, and an expanding investor base (International Renewable Energy Agency 2021).

On the other hand, environmental technologies, such as energy storage and smart grid systems, are also crucial for the successful integration of renewable energy sources into the energy mix. These technologies help to address the intermittency and variability of renewable energy sources and enable their more efficient use. As highlighted by the International Energy Agency (2021), renewable energy technologies can meet up to 90% of global electricity demand by 2050 with the help of these enabling technologies. Kucukvar et al. (2022) also demonstrated that the adoption of environmental technologies, such as wind and solar energy, can help Turkey reduce its carbon emissions and achieve sustainable energy transition.

The innovative intuition underlying the analysis is rooted in the paradoxical connection between economic sophistication and environmental viability in the emerging world. It is generally assumed in economic theory on the one hand, that the more complex the economic structure, the greater the efficiency of the economy, but on the other hand, this study leads to a hypothesis on a 'green structural lock-in' problem in the Turkish case. The implication is, perhaps, the more advanced the economic sophistication, the more the industrial structure is 'locked in' on fossil fuel-based industries, while the increased financial sophistication may even support this unsustainable path without proper green institutions. The aim of this analysis is to determine whether this problem functions as a catalyst or a brake for the Turkish transition towards a low-carbon economic system.

Despite these findings, Turkey faces significant challenges in transitioning to sustainable energy sources. These include issues such as energy market liberalization, lack of financing options, and policy and regulatory challenges. Therefore, the authors are motivated to investigate the effect of financial development and environmental technologies on the clean energy transition. In this regard, the authors intend to answer the question, what is the role of financial development and environmental innovations in Turkey's clean energy transition? The answer to this question can help policymakers and stakeholders make informed decisions about the allocation of resources and the development of sustainable policies and regulations.

This study contributes to the understanding of the energy transition process in Turkey by overcoming some limitations and deficiencies in earlier studies, particularly the one conducted by Mukhtarov et al. (2022), and provides three specific contributions:

- Measurement Advancement: In Mukhtarov et al. (2022, 172), 'total values of stocks traded as a percentage of GDP' was employed. As a proxy, this has limitations in determining the complex nature of the financial system. Instead, this paper applies an all-inclusive Financial Development Index, which embraces access, depth, and efficiency of both markets and institutions. This provides scope to segment and recognize institutional constraints that are actually obstructing the adoption of clean energy.
- Theoretical Novelty: The grouping of financial development, environmental innovations, and economic complexity into one empir-

ical model can now be clearly justified. This grouping is necessary in order to examine the 'green structural lock-in' hypothesis – the innovative hypothesis that the sophistication of industry and the magnitude of finance might paradoxically hinder the growth of renewables if the industry structures lock-in fossil fuel-scarce output.

- Methodological Rigour: The methodological novelty introduced in this research is the usage of the Fourier Bootstrap ARDL (FBARDL) method. The proposed Fourier Bootstrap ARDL method surpasses the ARDL or SVAR approaches of previous works. Unlike these previous works that yield biased structures with inconclusive cointegration analyses under small samples, the proposed approach is capable of handling up to five smooth structural break dynamics with robust critical values.

Scientifically, this paper contributes positively to the international discourse on energy transition by exemplifying the 'green paradox' found in emerging economies. This paper advances the scientific community beyond the understanding that finance and complexity are universally positive, as it clearly verifies that their effects rely on the structure of industries and the institutions found there. In providing the specific empirical example of Turkey, where the 1% increase in financial development and economic complexity supported the finding that renewable energy demand declines by about 1.12% and 0.70% respectively, this paper offers a necessary antidote to prevailing approaches on energy transition for non-OECD economies.

The structure of the study can be described as follows: Section 2 is a thematic synthesis of the existing literature on financial development, environmental technology, and economic complexity. In turn, Section 3 discusses the Fourier Bootstrap ARDL (FBARDL) approach and sources of the data. Section 4 presents the empirical findings, while Section 5 concludes with summarized policy suggestions.

Literature Review

FINANCIAL DEVELOPMENT AND RENEWABLE ENERGY

The link between financial development (FD) and renewable energy consumption (REC) is two-fold in the global literature. One school of thought argues that financial development encourages renewable energy consumption by reducing costs and mobilizing resources for sustainability, which is observed in high-income countries (Shahbaz et al.

2021), the BRICST region (Zhang and Razzaq 2022), and China (Li et al. 2023). In contrast, some researchers argue that the link between financial development and renewable energy consumption is non-linear/threshold-dependent: in 46 countries in Africa, financial development becomes an incentive only after the attainment of a certain level of institutional depth (Muoneke et al. 2023); in the US and Nigeria, the response of renewable energy demand is only to certain indicators like market access and multidimensional indices (Dimnwobi et al. 2022; Lahiani et al. 2021; Pata et al. 2022).

In terms of Turkey specifically, previous research using Autoregressive Distribute Lagged (ARDL) and Vector Error Correction Model (VECM) techniques indicated that FD and REC have a positive relationship (Mukhtarov et al. 2022). Nevertheless, these studies have been limited by their reliance on narrow measures of financial development, such as stock exchange turnover. In contrast, this research employs a wide-based index to establish the existence of an institutional bottleneck in Turkey. The negative relationship established in this research implies that Turkey's financial development has historically been without ESG-based governance structures and that its growth via exports has been driven by carbon-based industries rather than renewable energy projects (Zhao et al. 2025).

There exists a clear divide in financial development (FD) and renewable energy (REC) literature in general. Some bodies of literature indicate that financial development supports REC development in terms of lowering costs associated with capital. However, other bodies seem to indicate a non-linearity or a financial development with certain thresholds in terms of its effect on RECs. However, a gap exists in literature that focuses on Turkey, as it tends to use a limited stock market measure that is not multi-dimensional, failing to measure institutional efficiency adequately. The gap is filled by this research with a broad-based financial development index.

In summary, although there is a general consensus on the financial development literature supporting the use of renewable energy sources in the reduction of costs, there is a major disagreement on the nature of this dependency between the literature on the topic and the previous findings for the case of emerging countries. Furthermore, there is a crucial research gap, as the majority of the previous findings use a narrow proxy of stock market development instead of indices. This will address this issue, as this research aims to find out the particular institutional

barriers in the case of the country of Turkey that could cause a negatively affecting dependency on the adoption of clean energy.

ENVIRONMENTAL TECHNOLOGIES AND RENEWABLE ENERGY

The significance of environmental innovation as a catalyst for the shift towards clean energy sources through efficiency and cost savings has been validated globally. Global evidence indicates that technology patents and R&D investments remain significant factors in determining the energy intensity and demand of various countries, such as the BRICS and G7 countries (Solarin et al. 2022; Peng et al. 2022), Scandinavia, and Indonesia (Serener et al. 2023; Joof et al 2022; Murad et al. 2019; Saudi et al. 2019). Moreover, green technology and AI innovations remain instrumental in determining inequality in emissions and energy security (Bergougui et al. 2025).

In the case of Turkey, while R&D investments in renewable energy have been shown to improve environmental quality, urbanization and fossil fuel-based R&D activities continue to reduce the Load Capacity Factor (Caglar et al. 2024; Yavuz et al. 2024). Despite the global consensus on the positive impacts of eco-innovation on the environment and the shift towards a low-carbon economy, the impacts of PET on Turkey's unique energy equilibrium have remained under-explored until now. This paper fills the gap by identifying PET as the most reliable factor in determining the decarbonization process in Turkey despite the presence of significant hurdles.

What has emerged from the literature is the fact that environmental innovation has a strong positive effect on the promotion of the clean energy transition through efficiency enhancements and a reduction in costs. Though the positive relationship between the two factors is validated in the global context of the G7 and BRICS, the relationship between patent environmental technologies and the special energy structure of Turkey has yet to become fully exposed and assessed. The problem is resolved by isolating the Turkey energy equilibrium effect that supports the fact that environmental technologies are the most dependable factor of decarbonization processes despite the presence of difficulties offered by other factors.

Recent studies on Economic Complexity (EC) indicate paradoxical perspectives: although EC can promote energy efficiency in certain developed countries, it tends to be an impediment in emerging countries with fossil fuel-driven growth in industry. The 'complexity-energy par-

adox' indicated here implies that a country's development level can vary between 'impediment' and 'catalyst' in green transition, being contingent on a certain country's development level that this research aims to shed critical light on in Turkey, currently facing this paradox in industry–environmental relations.

ECONOMIC COMPLEXITY AND RENEWABLE ENERGY

Recent studies emphasize the presence of a 'complexity-energy paradox'. In developed OECD countries and the EU, EC is usually positively correlated with environmental sustainability and the reduction of CO_2 emissions through the promotion of energy efficiency (Balsalobre-Lorente et al. 2023; Khezri et al. 2022; Can and Ahmed 2022; Doğan et al. 2020). In contrast, in developing countries such as the BRICS countries or NICS, the presence of high industrial complexity can be considered an impediment to the development of environmental sustainability, given that the complexity in these countries is usually associated with carbon-intensive production (Zeraibi et al. 2023; Li et al. 2025).

This double-edged sword effect is the core of the Turkish case (Balsalobre-Lorente et al. 2022). Turkey's industrial complexity is considered to be highly sophisticated, yet the 'green structural lock-in' is present in the sense that the diversification of industries in the country has not yet taken place in the context of environmental sustainability (Doğan et al. 2021). This study aims to investigate whether the presence of industrial complexity in Turkey acts as a catalyst or an impediment in the development of environmental sustainability.

The literature pertaining to economic complexity has confirmed the presence of a double-edged sword effect. Thus, it can work as an effective force in developed economies regarding efficiency. However, it can become an obstacle in countries with industries that remain highly dependent on carbon-based consumption. This issue presents an important unanswered question related to Turkey's status with regard to the complexity-energy nexus. The question is answered through our research. We seek to examine whether Turkey's industrial complexity is compatible with or obstructs its green energy policies.

Findings from previous studies on Economic Complexity (EC have shown a grave mismatch, where, on one hand, EC supports efficiency in most OECD countries, while, on the other hand, it frequently proves to be an impediment for emerging economies that rely heavily on carbon-intensive consumption, as industries in these countries are still largely

driven by a carbon-intensive consumption pattern. Such a double-edged sword characteristic points to a pending issue with respect to Turkey's particular positioning in the complexity-energy relationship.

Methodology

The study examines the effect of financial development, environmental technology, and economic complexity on clean energy in Turkey using the Fourier Bootstrap Autoregressive Distributed Lag (FBARDL) on annual data from 1980–2020. The selected timeframe is based on data availability. However, the transformation of REC and PET into natural logarithms and the use of FD (Financial Development Index) and EC (Economic Complexity) in level form help to facilitate the analysis, and the use of natural logarithms would affect the institutional structure that the indices convey (equation 1):

$$\ln(REC_t) = \beta_0 + \beta_1 FD_t + \beta_2 \ln(PET_t) + \beta_3 EC_t + \nu_t, \quad (1)$$

TABLE 1 Variable Description and Data Sources

Variable	Symbol	Definition / Measurement	Primary Source
Renewable Energy	REC_t	Renewable energy consumption as a % of total final energy consumption	World Bank: World Development Indicators (WDI)*
Financial Development	FD_t	Financial Development Index (capturing depth, access, and efficiency of institutions and markets)	International Monetary Fund (IMF)**
Environmental Technologies	PET_t	Development of environment-related technologies (measured by patent counts)	OECD: Environment Statistics***
Economic Complexity	EC_t	Economic Complexity Index (EC) (measuring the knowledge intensity of an economy)	The Atlas of Economic Complexity (Harvard Growth Lab)****

NOTES All variables except for Financial Development (FD_t) and Economic Complexity (EC_t) are converted into their natural logarithmic forms for the empirical analysis. Also, the data covers the period 1980–2020 based on the maximum available data frequency for all indicators in Turkey.

* https://databank.worldbank.org/source/world-development-indicators

** https://data.imf.org/?sk=f8032e80-b36c-43b1-ac26-493c5b1cd33b

*** https://www.oecd.org/en/data/indicators/patents-on-environment-technologies.html

**** https://atlas.hks.harvard.edu/

TABLE 2 Descriptive Statistics

	FD	EC	PET	REC
Mean	0.405121	0.339607	7.184839	16.79263
Median	0.429519	0.327068	7.140000	15.33880
Maximum	0.539528	0.787538	11.51000	24.51078
Minimum	0.195825	0.091581	4.170000	11.40300
Std. Dev.	0.103531	0.183092	1.735928	4.589580
Skewness	−0.455815	0.476989	0.357872	0.496280
Kurtosis	2.084302	2.335771	2.737327	1.723335
Jarque-Bera	2.156530	1.745395	0.750830	3.377771
Probability	0.340185	0.417823	0.687004	0.184725

NOTE p-values for Jarque-Bera indicate that all series are normally distributed at the 5% level.

where REC_t is renewable energy, FD_t is financial development, PET_t is environmental technologies, EC_t is economic complexity and *** ν_t is the error term. Table 1 indicates the explanation of the variables.

The descriptive statistics (table 2) provides a complete summary of the four economic and environmental variables.

Renewable Energy Consumption (REC) has the highest central tendency measure with a mean of 16.79 and median of 15.34, together with the largest variability measured by the highest standard deviation of 4.59. FD and EC, on the other hand, both have lower means (0.41 and 0.34, respectively) with smaller variability. All the variables' distributions are positively skewed except FD, which is negatively skewed with a skewness measure of −0.46. The kurtosis measures of the variables all lie below 3, meaning the distributions are platykurtic with less extreme values compared to the normal distribution. Lastly, the outcome of the Jarque-Bera test, as denoted by the low statistics with high probability values (all above 0.05) for all the variables, fails to reject the null hypothesis concerning normality at the conventional significance levels.

MODEL ESTIMATION

The choice of the FBARDL model is based on two key factors. The first is the stationarity properties of the variables such as the financial development index, an I(0) variable, and clean energy which is an I(1), indicating mixed order of integration. Thus, the ARDL family models are appropriate. However, due to the limitations (weak power and size

problem) and the inclusiveness of the ARDL bound test (which occurs when the F-statistics fall between the upper and lower bounds), we use the Fourier Bootstrap ARDL which proposes additional F-statistics to resolve the inconclusiveness of the traditional ARDL. Furthermore, the bootstrapping provides robust inference and addresses small sample biases. Secondly, considering the various global events such as the Asia currency crisis in 1997, the 2008 global financial crises, and COVID-19 among others, we hypothesized the presence of structural breaks in the series. Thus, unlike the traditional ARDL, the FBARDL accounts for up to five smooth structural breaks.

Prior to the application of the FBARDL, we applied various preliminary tests. First, the Fourier Augmented Dickey-Fuller (FADF) and Fourier Phillips-Peron (FPP) unit root test which permits smooth structural breaks. The FADF incorporates the Fourier function into the traditional ADF to account for smooth structural breaks (Enders and Lee 2012). The FADF's deterministic form is given in equation (2):

$$a(t) = \alpha_0 + \gamma_1 \sin(2\pi ktT) + \gamma_2 \cos(2\pi ktT) \tag{2}$$

where k denotes the Fourier form number of frequency; in order to obtain the FADF unit root a deterministic term is added to the ADF process where k shows the frequency number of Fourier terms. The Fourier ADF unit root test model is obtained by adding the deterministic term to the ADF procedure (Enders and Lee 2012):

$$\begin{aligned}\Delta y_t = {} & \alpha_1 + \delta t + \beta y_{t-1} + \gamma_1 \sin(2\pi ktT) + \gamma_2 \cos(2\pi ktT) \\ & + \sum_{i=1}^{p} \vartheta_i \Delta y_{t-i} + u_t\end{aligned} \tag{3}$$

To maintain clarity on the choice of the Fourier components (k) for the data, the data-analytic approach recommended by Enders and Lee (2012) is employed. The results are estimated for a range of $1 \leq k \leq 5$. The choice of the optimal k is made by choosing the particular k that produces the smallest Residual Sum of Squares (RSS) among the estimated models. An F-test is then conducted to test the significance of the Fourier components, and if significant, the FADF test is said to be more encompassing than the standard unit root tests, ignoring structural breaks.

Moreover, the Akaike Information Criterion (AIC) is selected to determine the lag length in the ARDL process. The AIC choice ascertains that the model

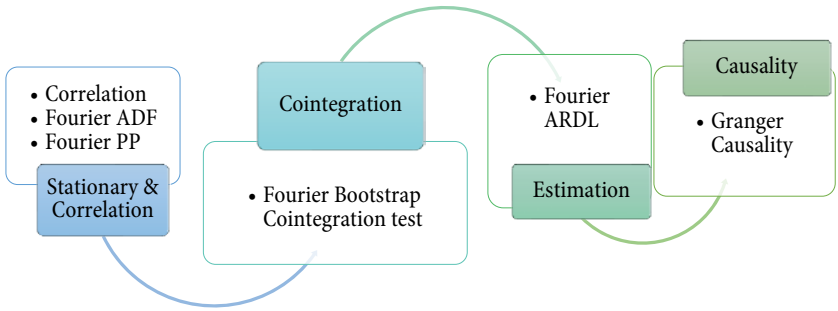


FIGURE 2 Methodological Structure

incorporates adequate lags to remove the serial correlation in the residuals and is parsimonious enough to avoid over-parameterization. Proceeding with this approach, the optimal lag structure was identified, for this analysis, by a configuration of (1, 0, 0, 0), as reflected in the estimation results.

In addition, the Fourier Bootstrap ARDL is applied to assess the cointegration among the variables. The Bootstrap ARDL (BARDL) was proposed by McNown et al. (2018) to resolve the limitations (weak power and size problem) of the traditional ARDL. Based on the ARDL when the F-statistics fall between the upper and lower bounds, the decision on cointegration is inconclusive; however, the BARDL eliminated this constraint by proposing additional F-statistics. The BARDL provides three F-statistics: (i) t-independent is for the lagged independent variable (ii) t-dependent is the lagged value of dependent variable, and (iii) overall F statistics (McNown et al. 2018). However, the BARDL does not account for breaks, thus, Solarin et al. (2022) developed the Fourier BARDL to account for smooth structural breaks as revealed in equation (4):

$$\begin{aligned}\Delta REC_t = \alpha_0 &+ \sum_{i=1}^{P-1} \alpha_1 \Delta REC_{t-i} + \sum_{i=1}^{q-1} \alpha_2 \Delta FD_{t-i} + \sum_{i=1}^{u-1} \alpha_3 \Delta PET_{t-i} \\ &+ \sum_{i=1}^{u-1} \alpha_4 \Delta EC_{t-i} + \beta_1 REC_{t-1} + \beta_2 FD_{t-1} + \beta_3 LPET_{t-1} \\ &+ \beta_4 EC_{t-1} + \beta_5 \sin\left(\frac{2\pi kt}{T}\right) + \beta_6 \cos\left(\frac{2\pi kt}{T}\right) + \nu_t .\end{aligned} \tag{4}$$

The cointegration among the series is established when all the three F-statistics are higher than the critical values of the bootstrap. Finally, we estimated the long and short run Fourier ARDL model. Figure 2 presents the methodological structure.

Data and Empirical Results

CORRELATION TEST

The correlation matrix is presented in table 3. The results suggest the absence of multicollinearity amid the explanatory indicators, hence the coefficients are < the 0.8 rule of thumb. Moreover, the outcome also revealed that FD has a negative significant association with REC; however, environmental technology was found to improve renewable energy consumption at 1% significance. The level of economic complexity has a negative significant effect on REC.

TABLE 3 Correlation Matrix Analysis

	REC	FD	PET	EC
REC	1	−0.9516***	0.1677***	−0.7760***
FD		1	−0.1847	0.7712***
PET			1	−0.1698
EC				1

NOTE FD is financial development, EC is economic complexity, PET is environmental technologies. *** signifies 1% significance level.

FOURIER UNIT ROOT TEST

Table 4 reported the Fourier ADF and PP unit root test; the outcome revealed that financial development, renewable energy and economic complexity contain unit root at level I(0) but are stationary at first difference I(1). However, environmental technology is stationary at I(0). This indicates the presence of mixed cointegration between the variables, i.e. I(0) and I(1). The null hypothesis of unit root is rejected when the P value is less than the 5% significance level.

TABLE 4 Fourier Unit Root Test Results

Variables	Fourier-ADF		Fourier-PP		Decision	*K*	*P*
	I(0)	I(1)	I(0)	I(1)			
REC	−1.3742	−5.9453***	−2.3915	−7.1873***	I(1)	2	1
FD	−2.0513***	–	−2.6415	−7.8787***	I(0)/ I(1)	1	1
PET	−3.2431***	–	−4.1437***	–	I(0)	5	1
EC	−1.7052	−6.7162***	−1.4606	−4.4544***	I(1)	1	1

NOTE *K* represents the number of smooth structural breaks; *P* is the Fourier frequency; *** shows 1% significance level. The Decision column confirms the mixed integration order of I(0) and I(1).

FOURIER BOOTSTRAP COINTEGRATION

In table 5 we reported on the Fourier Bootstrap cointegration test. This approach resolves the limitations (weak power and size problem) and the inclusiveness of the ARDL bound test which occurs when the F-statistics fall between the upper and lower bounds, by proposing additional F-statistics, and also accounting for smooth structural breaks. The outcomes suggest the presence of long-run cointegration between the series. The three F-statistics are higher than the bootstrap cointegration critical values at a 5% level of significance.

TABLE 5 Fourier Bootstrap Cointegration Test

Statistics	Critical Values				
	Value	10%	5%	1%	Decision
F-stat.	6.7854**	5.0444	5.9388	9.3348	
t-dep.	−4.7837**	−3.0813	−3.5611	−4.5345	√
F-indep.	3.9707**	2.9707	3.7414	6.0773	

NOTE ** denotes 5% significance level.

DISCUSSION OF FINDINGS AND COMPARATIVE ANALYSIS

Our empirical results strongly support the intuitive 'green structural trap'. The statistically significant negative impact of both financial development and economic complexity points to the fact that the current growth model of Turkey is still deeply rooted in traditional, energy-intensive sectors. This means that an increase in the volume of finance or complexity of products is not sufficient but rather the direction of those factors towards green innovation is what really matters for the success of the energy transition.

The Fourier ARDL estimations are presented in table 6; the outcome showed an inverse significant lagged error correction term (ECT (−1)), indicates 86% speed of adjustment which the system converges in the long run. The short and long-run estimations revealed that the level of FD in Turkey has a negative effect on REC. The result further indicates that a 1% increase in financial development decreases renewable energy use in Turkey by 0.94% and 1.12% in the short and long run, respectively. The negative impact of financial development (FD) on clean energy in Turkey reveals a specific institutional bottleneck. Unlike developed economies, Turkey's financial expansion has historically favoured carbon-intensive sectors that serve as the backbone of its export-driven economy. Furthermore, high borrowing costs in the Turkish economy

TABLE 6 Fourier ARDL

Variable	Short run		Long run	
	Coefficient	*p*-values	Coefficient	*p*-values
FD	−0.9393	0.0034**	−1.1211	0.0343**
PET	0.1039	0.0000***	0.1211	0.0009***
EC	−0.6034	0.0011***	−0.7047	0.0003***
ECT (−1)			−0.8562	0.0000***
Diagnostics				
Statistics			Coefficients	p-values
LM serial correlation			1.0612	0.3647
Breusch–Pagan–Godfrey			1.7881	0.1481
Normality			0.6868	0.6336

NOTE The Fourier ARDL (1, 0, 0, 0) was estimated. FD is financial development, EC is economic complexity, PET is environmental technologies. ***, ** signifies 1% and 5% significance level.

make it difficult to fund renewable energy projects, which often require more capital-intensive maintenance than conventional fossil-fuel sources. This negative relationship between financial development and clean energy is contradicted by the study of Mukhtarov et al. (2022), who examine the link between financial development and clean energy in Turkey from 1980–2019 using the ARDL and VECM and found financial development enhances the level of clean energy usage. Likewise, Dimnwobi et al. (2022) in the case of Nigeria, Seraj and Seraj (2025) across 15 of the world's highest carbon-emitting countries and Oben et al. (2025) in the case of Morocco.

These results show that for every 1% economic complexity, there is a resulting 0.70% reduction in overall renewable energy use in the Turkish economy. Turkey's current industrial sophistication is energy-intensive and remains carbon-locked into conventional sources. The country faces a complexity trap where its high industrial complexity is not matched by domestic green tech endowments, forcing a reliance on energy-intensive production and imported renewable technology to meet growth targets. Although most of the literature found that economic complexity promotes clean energy consumption (for instance: Doğan et al. (2020) in OECD countries, Li et al. (2023) in newly industrialized nations (NICS), Ghosh (2025) in G7 nations, Balsalobre-Lorente et al. (2022) in in PIIGS economies, and Wang et al. (2025) in 151 Chinese cities): our findings suggested the reverse in Turkey. The inverse relationship between economic complexity found in our study could be explained by the fact that

Turkey heavily relies on imported renewable energy technologies due to its limited technological capabilities, which makes it more difficult to develop a sustainable domestic renewable energy industry.

On the other hand, environmental technology enhances clean energy usage in Turkey. Ceteris paribus, a surge in environmental technology augments the level of renewable energy by 0.10% in the short run and 0.12% in the long run. Turkey has been investing in environmental technologies (wind, solar and geothermal power plants) to improve efficiency and reduce the cost of clean energy. As a result, clean energy has become more competitive and has increased its share in Turkey's energy mix.

To put these results in a better perspective, table 7 compares and contrasts our findings with the existing literature. Our findings clearly diverge from the 'positive-finance' consensus, e.g. Mukhtarov et al. (2022), both statistically, methodologically, and conceptually. Methodologically, by utilizing the FBARDL approach, we account for Turkey's specific structural shifts that traditional models ignore. Conceptually, our findings confirm that Turkish industrial evolution has not yet reached the turning point where sophistication yields environmental efficiency, a dynamic that differentiates Turkey from the established patterns observed in G7 or OECD countries.

Our findings are in support of the following studies: Murad et al. (2019), for the case of Denmark, found that innovation and energy prices are key determinants of energy utilization. Likewise, Saudi et al. (2019) in Indonesia found that innovation is a key indicator of energy intensity. Also, the study of Jin et al. (2018) in China revealed that innovation augments clean energy demand. We also conducted diagnostics such as the Breusch–Pagan–Godfrey LM test of serial correlation, ARCH test for heteroskedasticity and normality, CUSUM and CUSUM of square tests to affirm the stability and reliability of our model. The outcome showed that

TABLE 7 Summary of Comparative Findings

Variable	Our Finding (Turkey)	Previous Literature	Nature of Contrast/Alignment
Financial Development	Negative	Positive (Mukhtarov et al. 2022)	Contrast: Our broad-based index identifies institutional bottlenecks.
Economic Complexity	Negative	Mixed/Positive (Doğan et al. 2020)	Contrast: Suggests industrial 'lock-in' to fossil fuels.
Environmental Technologies	Positive	Positive (Murad et al. 2019)	Consensus: Innovation remains the primary driver of green growth.

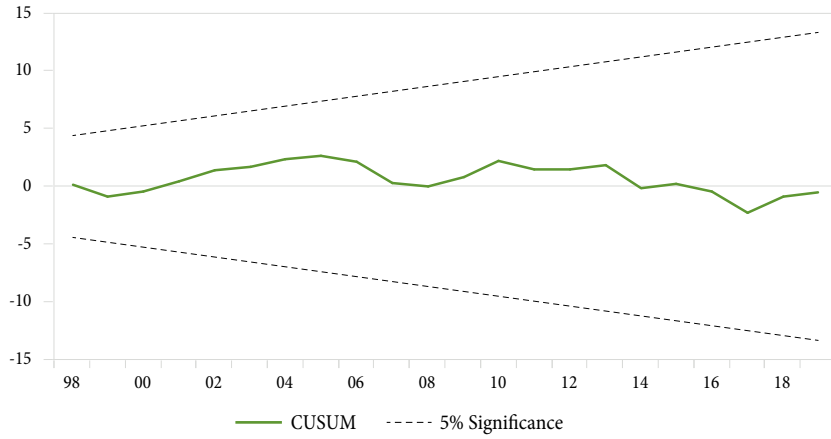


FIGURE 3 CUSUM Stability Test

NOTE The blue line represents the cumulative sum of recursive residuals. The red dashed lines represent the 5% significance boundaries. As the blue line remains within the boundaries, the model is confirmed stable.

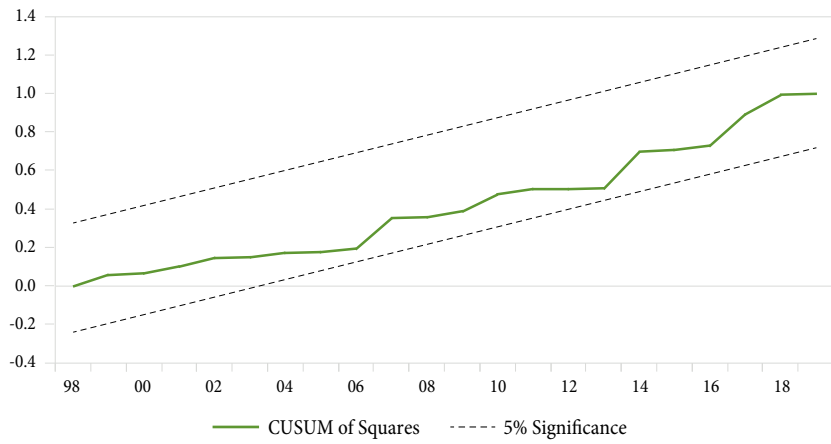


FIGURE 4 CUSUM of Square Test

NOTE The blue line represents the cumulative sum of recursive residuals. The red dashed lines represent the 5% significance boundaries. As the blue line remains within the boundaries, the model is confirmed stable.

the p values are higher than the 5% confidence level, thus indicating that our model is not suffering from serial correlation or heteroskedasticity and the variables are normally distributed. Likewise, the CUSUM and CUSUM of square tests (figs. 3 and 4) also revealed that the model is stable because the red line lay within the 5% confidence levels.

GRANGER CAUSALITY TEST

Results of the Granger Causality Test, as shown in table 8 below, offer key directional information necessary for interpreting the results of the Fourier ARDL analysis. A one-way causal relationship was determined to exist and run from the financial development variable to the renewable energy consumption variable. This confirms that the negative relationship between FD and REC is not just one-way but that the growth of the financial system of Turkey directly impacts the energy structure, perpetuating the trend of following carbon-emitting industries and not the renewable ones.

A similar process of a one-way reaction from environmental technology to the consumption of renewable energy further accentuates the positive and proactive role of PET as a catalyst for the decarbonized transformation of the Turkish economy. This absence of causality with a zero result from economic complexity and the consumption of renewable energy adds a slight twist of complexity in the context of the ARDL findings. The negative results for EC in the context of the simplified model imply a decoupling of the highly sophisticated industrial process of the country with the green energy vision.

TABLE 8 Causality Test

Null hypothesis	*F*-statistics	*p*-value
REC ← FD	3.5644	0.0698**
	0.9273	0.3441
REC ≠ PET	0.4221	0.5216
	2.2718	0.1356
REC ← PET	4.0822	0.0166**
	0.1627	0.6898

NOTE FD is financial development, EC is economic complexity, PET is environmental technologies. ** Signifies 5% significance level.

Conclusions and Policy Recommendations

This study employs the recently developed Fourier Bootstrap ARDL (FBARDL) model to investigate Turkey's clean energy transition between 1980 and 2020. The results of this study support the existence of a 'green structural trap' phenomenon. Firstly, financial development (FD) has a strong negative impact on REC. A 1% increase in financial development causes a 1.12% decrease in REC. This suggests that Turkey's financial system, with its high interest rates and carbon-locked institutional lending,

is unable to cope with the risks of using renewable energy. Secondly, the 'complexity-energy paradox' is also evident, as Turkey's increasing economic complexity is locked into carbon-intensive technology and hence acts as a barrier to clean energy transition. By contrast, environmental technology (PET) is the main driver of clean energy transition, with a 1% increase in PET increasing REC by 0.12%.

PRACTICAL AND POLICY IMPLICATIONS

From a policy point of view, the transition is faced with institutional bottlenecks. Turkish policymakers need to adopt directional green finance by creating a Green investment bank to lower interest costs, particularly for renewable SMEs. In addition, R&D tax breaks need to target the automobile and petrochemical industries to separate the sophistication of industry from the consumption of fossil fuels. This is necessary to overcome the complexity trap and ensure that Turkey's growth strategy is consistent with its sustainable energy commitments.

LIMITATIONS AND DIRECTIONS FOR FUTURE RESEARCH

Despite the methodological rigour, this study has some limitations. The study is constrained by the availability of data from 1980 to 2020. In addition, although we used a financial development index, our empirical focus is on index-driven growth rather than institutional factors such as regulatory and political stability.

Future research may extend this research by conducting more country-specific analyses on emerging economies to test if the 'green structural trap' is a common feature among non-OECD economies worldwide. Future models may also use the Clean Energy Transition Index or panel data methods to account for regional trends. Analysing the effect of liberalized energy markets and green finance obligations on various sectors may offer more detailed insights into Turkey's journey to a zero-carbon electricity source.

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