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The Impact of Renewable Energy Investment and Economic Openness on Reducing Carbon Emissions as a Preliminary Step for the Transition Towards Green Hydrogen in Algeria: An Econometric Study

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ABSTRACT

This study examines the dynamic effects of renewable energy consumption, economic growth, foreign direct investment (FDI) and trade openness on carbon dioxide (CO_2) emissions in Algeria over 1990–2023, as an empirical step preceding the country's prospective shift from grey to green hydrogen. Using an autoregressive distributed lag (ARDL) model, specified as ARDL(1,1,2,2,2) on the basis of the Akaike information criterion, and the bounds-testing procedure of Pesaran et al. (2001), we find evidence of a long-run equilibrium relationship among the variables ($F = 5.395$, above the upper critical bound at the 1% level). The error-correction coefficient (-0.4745, significant at the 1% level) indicates that about 47% of any deviation from the long-run path is corrected within one year. The long-run estimates show a large negative output elasticity of emissions (-1.513), consistent with the onset of decoupling, and a negative elasticity with respect to trade openness (-0.155), whereas renewable energy consumption (+0.093) and FDI (+0.061) carry positive coefficients, which we interpret as reflecting an early transitional stage of the energy system and the concentration of capital inflows in energy-intensive activities. Residual diagnostics and stability tests do not indicate serial correlation, heteroskedasticity, non-normality or parameter instability. The findings suggest that renewable deployment, as currently configured, is not yet sufficient to decarbonise the economy, and that a green hydrogen strategy will depend on prior and additional renewable capacity, investment screening and a trade policy that favours clean technologies.

Keywords: CO_2 emissions; renewable energy; economic growth; ARDL model; cointegration; green hydrogen; Algeria

JEL classification: C22, Q43, Q56

1. INTRODUCTION

Climate change has become one of the defining economic challenges of the twenty-first century. The Sixth Assessment Report of the Intergovernmental Panel on Climate Change concludes that human influence has unequivocally warmed the atmosphere, oceans and land, with carbon dioxide (CO_2) from fossil-fuel combustion and industrial processes being the largest single contributor to anthropogenic radiative forcing (IPCC, 2021). The economic stakes are considerable: the Stern Review (2006) argued that the costs of inaction would far exceed the

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costs of early mitigation, while integrated-assessment work such as Nordhaus (2008) has made the trade-off between abatement costs and avoided damages central to the design of climate policy.

Reconciling economic growth with environmental sustainability is therefore a central question for developing and emerging economies. The green economy paradigm promoted by the United Nations Environment Programme (UNEP, 2011) places renewable energy deployment, cleaner technologies and efficient resource use at the core of this reconciliation. Within this paradigm, three macro-level channels are widely discussed: the diffusion of renewable energy; the inflow of foreign direct investment (FDI), which may carry capital, technology and management practices; and trade openness, which shapes specialisation patterns and technology transfer. Whether these channels reduce or aggravate emissions is, however, an empirical question whose answer depends on the structure of the host economy and on its regulatory environment.

Algeria offers an instructive setting. Its economy remains heavily dependent on hydrocarbons for export earnings, fiscal revenues and domestic energy supply, and its electricity system is overwhelmingly fuelled by natural gas. At the same time, the country has articulated an ambitious transition agenda: a national renewable programme of 15 GW of installed capacity, with 2035 as the horizon in recent official communications (Algeria Invest, 2026), and a National Hydrogen Development Strategy presented by the Ministry of Energy and Mines (2023) that targets renewable (green) hydrogen alongside low-carbon hydrogen. Algeria is also a prospective supplier to the European market through the proposed SoutH2 Corridor, a planned 3,300 km pipeline network designed largely around repurposed gas infrastructure (Green Hydrogen Organisation, n.d.). Moving from natural-gas-based (grey) hydrogen to hydrogen produced by water electrolysis with renewable electricity is environmentally meaningful only if the underlying power system itself decarbonises; otherwise, electrolysis merely relocates emissions. Understanding how renewable energy, growth, FDI and trade have shaped Algerian CO_2 emissions to date therefore provides an empirical baseline for assessing the readiness of the economy for a hydrogen-based transition.

Existing studies on Algeria have examined the emissions–growth relationship and the role of electricity consumption (Bouznit & Pablo-Romero, 2016; Belaïd & Youssef, 2017), but, to our knowledge, evidence that jointly considers renewable energy consumption, FDI and trade openness within a single ARDL framework, and that interprets the results with an explicit view to the hydrogen transition, remains limited. This paper seeks to fill that gap.

Specifically, the study addresses three research questions: (i) Is there a long-run equilibrium relationship between CO_2 emissions and renewable energy consumption, economic growth, FDI and trade openness in Algeria over 1990–2023? (ii) How quickly do emissions return to this equilibrium after a shock? (iii) What are the signs and magnitudes of the long-run elasticities, and what do they imply for energy and investment policy in the run-up to a green hydrogen economy? The paper contributes in three ways. It provides time-series evidence for Algeria on four major macro-level determinants of emissions estimated simultaneously; it explicitly links the empirical findings to the policy debate on the grey-to-green hydrogen transition; and it documents the robustness of the estimated model through a full set of diagnostic and stability tests. The remainder of the paper is organised as follows. Section 2 presents the theoretical framework and develops the hypotheses; Section 3 describes the data and the empirical strategy; Section 4 reports the results; Section 5 discusses them; and Section 6 concludes with policy implications and limitations.

2. THEORETICAL FRAMEWORK AND LITERATURE REVIEW

2.1 Economic growth, environmental pressure and the decoupling hypothesis

The relationship between economic activity and environmental pressure has long been framed through the IPAT identity (Ehrlich & Holdren, 1971), which decomposes environmental impact into population, affluence and technology, and through its stochastic extension STIRPAT (York et al., 2003), which allows the elasticity of impact with respect to each driver to be estimated empirically. In this tradition, higher output raises emissions through a scale effect unless it is offset by changes in the composition of output and in the techniques of production.

The environmental Kuznets curve (EKC) hypothesis formalises this reasoning by positing an inverted-U relationship between income and pollution (Grossman & Krueger, 1995; Panayotou, 1997). Early in development,

the scale effect dominates; at higher income levels, structural shifts towards services and cleaner industries, rising demand for environmental quality and stricter regulation can reduce emissions. The EKC has nonetheless been criticised on econometric and conceptual grounds: the turning point is sensitive to model specification, the pattern differs across pollutants, and a decline in emissions is not an automatic by-product of growth but depends on policy and institutional choices (Stern, 2004).

A related and more policy-oriented notion is decoupling, which describes a situation in which output grows while environmental pressure grows more slowly (relative decoupling) or falls (absolute decoupling) (OECD, 2002). The empirical literature is cautious. Haberl et al. (2020) review the available evidence and conclude that absolute decoupling of GDP from greenhouse-gas emissions has been achieved in only a limited number of cases and at rates insufficient to meet ambitious climate targets, while Parrique et al. (2019) argue that decoupling alone is unlikely to deliver the reductions required. For a hydrocarbon-exporting economy such as Algeria, the sign of the long-run output elasticity of emissions is thus genuinely open: a positive sign would indicate that scale effects prevail, whereas a negative sign would be consistent with decoupling driven by structural and technological change.

2.2 Renewable energy and carbon emissions

Renewable energy can reduce emissions by displacing fossil-fuel generation and lowering the carbon intensity of the energy mix. The magnitude and timing of this effect, however, depend on how much fossil generation is actually displaced rather than supplemented, on the availability of grid flexibility and storage for variable sources, and on the emissions embodied in manufacturing, transporting and installing equipment. In the early stages of deployment, a small renewable share may be insufficient to alter the aggregate carbon intensity, and construction-related activity can temporarily raise emissions. Rebound effects, whereby cheaper clean power stimulates additional consumption, may further dampen net savings.

Empirical findings reflect this heterogeneity. Sadorsky (2009) shows that income and emissions are significant drivers of renewable energy consumption in emerging economies, underscoring the two-way interaction between development and the energy mix, and Apergis and Payne (2010) document a bidirectional causal relationship between renewable energy consumption and growth in OECD countries. Studies focusing directly on emissions generally report mitigating effects in countries with sizeable renewable shares: Bilgili et al. (2016) find that renewable energy consumption reduces CO_2 emissions in OECD countries within an EKC framework, and Dogan and Seker (2016) reach a similar conclusion for the leading renewable-energy countries while also highlighting the emission-increasing role of non-renewable energy. For Algeria, Belaïd and Youssef (2017) apply an ARDL approach to the links among emissions, renewable and non-renewable electricity consumption and growth, and find that growth and non-renewable electricity consumption damage environmental quality in the long run whereas renewable electricity use is beneficial. Bouznit and Pablo-Romero (2016), also using an ARDL model, find that energy and electricity consumption raise emissions and that the income level at which the EKC turns is very high, so that growth in Algeria is likely to keep increasing emissions. Evidence for Algeria is thus mixed and is based on samples that largely pre-date the recent expansion of renewable capacity.

2.3 Foreign direct investment and the environment

The effect of FDI on environmental quality is contested. The pollution haven hypothesis predicts that stringent regulation in advanced economies induces the relocation of pollution-intensive activities to countries with weaker standards (Copeland & Taylor, 1994, 2004), so that FDI raises host-country emissions. The pollution halo argument, in contrast, holds that multinational firms bring cleaner technologies, more efficient production processes and better environmental management, which can lower emissions in the host economy; early evidence for Latin America likewise challenged the haven hypothesis, finding that trade liberalisation and foreign investment were not associated with pollution-intensive industrial development (Birdsall & Wheeler, 1993). Empirical results are accordingly mixed. Omri et al. (2014) find bidirectional causality between FDI and CO_2 emissions in most panels of a global sample of 54 countries; Zhang and Zhou (2016) report evidence supporting the pollution halo hypothesis across Chinese regions; and Al-mulali and Tang (2013) find a long-run negative relationship between FDI inflows and CO_2 emissions in the Gulf Cooperation Council countries, concluding that energy consumption and growth, rather than FDI, drive pollution there. The net effect thus hinges on the sectoral composition of inflows and on the quality of environmental regulation: in resource-rich economies, inflows

concentrated in extractive and energy-intensive sectors are more likely to raise emissions, whereas inflows directed to renewable energy and low-carbon manufacturing can have the opposite effect.

2.4 Trade openness and emissions

Trade openness affects emissions through the scale, composition and technique effects distinguished by Antweiler et al. (2001) and Copeland and Taylor (2004): trade expands economic activity (scale), reallocates production according to comparative advantage (composition), and facilitates the diffusion of cleaner technologies while raising income-driven demand for environmental quality (technique). Frankel and Rose (2005) find that trade tends to improve some measures of environmental quality once income and institutional factors are controlled for, whereas Managi et al. (2009) show that the effects differ between OECD and non-OECD countries and across pollutants, with openness more likely to be detrimental in the latter group. For a developing exporter of hydrocarbons, the composition effect may work against the environment, while the import of efficient capital goods and clean technologies may work in its favour, so that the net sign is an empirical matter.

2.5 Green hydrogen and the Algerian context

Hydrogen is an energy carrier whose climate impact depends on its production route. Grey hydrogen is produced from natural gas by steam methane reforming without carbon capture; blue hydrogen uses the same process combined with carbon capture and storage; and green hydrogen is produced by electrolysing water with electricity from renewable sources (IEA, 2019). Green hydrogen is regarded as a key option for decarbonising hard-to-abate sectors such as heavy industry, shipping, aviation and chemicals, where direct electrification is difficult (IEA, 2019; IRENA, 2022). Its cost competitiveness is determined mainly by the cost of renewable electricity and the capacity factors of the generating assets, which gives regions with excellent solar and wind resources a potential comparative advantage (IRENA, 2022).

Algeria combines large solar and wind potential, an extensive gas-transport network that may be partly repurposed, and proximity to European demand centres. The national strategy presented by the Ministry of Energy and Mines (2023) is built around the expansion of solar photovoltaic and wind capacity, and the SoutH2 Corridor project envisages exporting hydrogen to Europe through a pipeline network of about 3,300 km, around 70% of which would consist of repurposed natural gas pipelines (Green Hydrogen Organisation, n.d.). These ambitions raise a macro-level question that is logically prior to the economics of individual hydrogen projects: does the Algerian economy already exhibit the conditions under which renewable energy, trade and capital inflows contribute to lower emissions? If, for example, the renewable share is still too small to alter the carbon intensity of the economy, or if FDI is concentrated in energy-intensive sectors, large-scale electrolysis could in the near term rely on a carbon-intensive power system. The empirical analysis that follows is designed to shed light on these preconditions; it does not model hydrogen production directly.

2.6 Hypotheses

On the basis of the preceding discussion, we test the following hypotheses, whose expected signs and underlying mechanisms are summarised in Table 1.

H1. There is a long-run equilibrium (cointegrating) relationship between CO_2 emissions and the set of explanatory variables; the null hypothesis is the absence of such a relationship.

H2. Renewable energy consumption affects CO_2 emissions in the long run; the sign is expected to be negative once the renewable share is large enough, but may be positive at an early transitional stage.

H3. Economic growth affects CO_2 emissions in the long run; a negative sign would be consistent with decoupling.

H4. FDI affects CO_2 emissions in the long run; a positive sign supports the pollution haven hypothesis and a negative sign the pollution halo hypothesis.

H5. Trade openness affects CO_2 emissions in the long run; the sign is expected to be negative if technique and composition effects dominate.

Table 1. Expected long-run effects on CO_2 emissions and theoretical mechanisms

Variable	Expected sign	Main theoretical mechanisms	Key references
lnREC	Negative (positive at early transition)	Fuel substitution and lower carbon intensity vs. embodied emissions, rebound effects and a small initial share	Bilgili et al. (2016); Dogan & Seker (2016)
lnGDP	Ambiguous (negative under decoupling)	Scale effect (+) vs. composition and technique effects (−)	Grossman & Krueger (1995); Stern (2004)
lnFDI	Positive (haven) or negative (halo)	Relocation of polluting activities vs. transfer of cleaner technologies	Copeland & Taylor (1994); Birdsall & Wheeler (1993); Zhang & Zhou (2016)
lnOPEN	Negative if technique and composition effects dominate	Technology diffusion and specialisation vs. scale expansion and transport intensity	Antweiler et al. (2001); Frankel & Rose (2005); Managi et al. (2009)

Source: Authors' synthesis of the literature reviewed in Section 2.

3. DATA AND METHODOLOGY

3.1 Data and variables

The analysis uses annual time series for Algeria covering 1990–2023, which yields 34 observations. The series are drawn from the World Bank's World Development Indicators (WDI) and from official energy and environment statistics. The sample spans several economic cycles and, although modest in size, is of a length typical of ARDL applications to annual country data. All variables are expressed in natural logarithms, so that the estimated coefficients can be read directly as elasticities. Table 2 defines the variables.

Table 2. Variables, definitions and sources

Variable	Symbol	Definition (natural logarithm)	Source
CO_2 emissions (dependent)	lnCO_2	Carbon dioxide emissions, a measure of the environmental burden	WDI
Renewable energy consumption	lnREC	Renewable energy consumption as a share of total energy consumption	WDI
Economic growth	lnGDP	Real gross domestic product, a measure of the scale of economic activity	WDI
Foreign direct investment	lnFDI	Net inflows of foreign direct investment	WDI
Trade openness	lnOPEN	Sum of exports and imports as a percentage of GDP	WDI

Source: Authors' compilation. WDI = World Development Indicators, World Bank.

3.2 Model specification

The long-run relationship is specified in double-logarithmic form, which attenuates heteroskedasticity and delivers elasticities directly:

$$lnCO_{2t} = \beta_0 + \beta_1\, lnREC_t + \beta_2\, lnGDP_t + \beta_3\, lnFDI_t + \beta_4\, lnOPEN_t + \varepsilon_t \quad (1)$$

where β_0 is the intercept, β_1–β_4 are the long-run elasticities of emissions with respect to renewable energy consumption, output, FDI and trade openness, and ε_t is a white-noise error term.

To estimate this relationship while allowing for short-run dynamics, we employ the ARDL bounds-testing approach of Pesaran and Shin (1999) and Pesaran et al. (2001). The approach has three features that suit the present application: it can be applied irrespective of whether the regressors are I(0) or I(1), provided that none is integrated of order two; it estimates short- and long-run parameters in a single equation; and, with appropriate lag selection, it performs relatively well in small samples (Narayan, 2005). The unrestricted error-correction model (UECM) is

$$\Delta lnCO_{2t} = \alpha_0 + \rho\, lnCO_{2t-1} + \Sigma_{j=1}^{4}\, \theta_j\, lnX_{j,t-1} + \Sigma_{i=1}^{p-1}\, \psi_i\, \Delta lnCO_{2t-i} + \Sigma_{j=1}^{4}\, \Sigma_{i=0}^{q-1}\, \varphi_{ji}\, \Delta lnX_{j,t-i} + u_t \quad (2)$$

where Δ is the first-difference operator, X_j denotes the four regressors (lnREC, lnGDP, lnFDI and lnOPEN), p and q are the lag orders, and u_t is the error term. The coefficient ρ on the lagged dependent variable is the speed-of-adjustment (error-correction) term and is expected to lie between −1 and 0; the θ_j are the long-run parameters; and ψ and φ capture short-run dynamics.

Cointegration is tested through the F-statistic for the joint null hypothesis H_0: $\rho = \theta_1 = \theta_2 = \theta_3 = \theta_4 = 0$ against the alternative that at least one of these coefficients is non-zero. The statistic has a non-standard distribution, and Pesaran et al. (2001) tabulate a lower bound (all regressors I(0)) and an upper bound (all regressors I(1)). If F

exceeds the upper bound, the null is rejected irrespective of the integration order of the regressors; if it falls below the lower bound, the null cannot be rejected; between the two bounds the test is inconclusive. We use the bounds for case III (unrestricted intercept, no trend). Long-run elasticities are recovered as $\delta_j = -\theta_j/\rho$.

3.3 Estimation procedure

The estimation proceeds in five steps: (i) augmented Dickey–Fuller (ADF) tests (Dickey & Fuller, 1979) to determine the integration order of each series and to rule out I(2) variables; (ii) selection of the lag structure by the Akaike information criterion (AIC; Akaike, 1974), with a maximum of two lags for each variable to preserve degrees of freedom given the sample size; (iii) the bounds test for cointegration; (iv) estimation of the UECM and of the long-run multipliers; and (v) diagnostic checking through the Breusch–Godfrey serial-correlation test (Breusch, 1978; Godfrey, 1978), the Breusch–Pagan heteroskedasticity test (Breusch & Pagan, 1979), the Jarque–Bera normality test (Jarque & Bera, 1987) and CUSUM-type parameter-stability tests (Brown et al., 1975). All computations were carried out in R.

4. EMPIRICAL RESULTS

4.1 Unit-root tests

The first step is to verify that no series is integrated of order two, since the critical bounds of Pesaran et al. (2001) are not valid in that case. Table 3 reports the ADF results at levels and in first differences.

Table 3. Augmented Dickey–Fuller unit-root tests

Variable	Level: t-statistic	Level: p-value	First difference: t-statistic	First difference: p-value	Order of integration
$\ln CO_2$	−2.414	0.412	−3.785	**0.034**	I(1)
lnREC	−3.108	0.143	−4.207	**0.013**	I(1)
lnGDP	−2.148	0.515	−3.359	**0.080**	I(1)
lnFDI	−1.681	0.696	−2.979	0.194	I(1) (provisional)
lnOPEN	−0.685	0.961	−3.943	**0.023**	I(1)

Source: Authors' estimations using R. Note: p-values in bold are below 0.10. For lnFDI, the first-difference p-value does not allow rejection of a unit root at conventional levels, so its classification as I(1) is provisional (see Section 6.3).

At levels, the p-values of all five series exceed 0.10, so the null hypothesis of a unit root cannot be rejected: the series are non-stationary in levels. In first differences, the null is rejected at the 5% level for $\ln CO_2$, lnREC and lnOPEN, and at the 10% level for lnGDP ($p = 0.080$). For lnFDI, the first-difference p-value (0.194) does not allow rejection at conventional levels; its classification as I(1) is therefore provisional, and the ADF evidence against an I(2) process is weaker for this variable than for the others. With this caveat, no series is found to be I(2) and the ARDL bounds approach can be applied.

4.2 Lag-length selection

Lag orders were selected automatically by the AIC, which performs well in small and medium samples, with a maximum of two lags per variable. The selected specification is ARDL(1,1,2,2,2) (Table 4): emissions depend on their own first lag; renewable energy consumption enters with its current value and one lag; and output, FDI and trade openness enter with their current values and up to two lags. This dynamic structure is economically plausible, since the effects of energy policy, investment and trade on emissions are unlikely to materialise entirely within the year in which they occur.

Table 4. Optimal lag orders of the ARDL model

Variable	Optimal lag order	Selection criterion
$\ln CO_2$	1	AIC
lnREC	1	AIC
lnGDP	2	AIC

Table 4. Optimal lag orders of the ARDL model *(continued)*

Variable	Optimal lag order	Selection criterion
lnFDI	2	AIC
lnOPEN	2	AIC

Source: Authors' estimations using R. Selected model: ARDL(1,1,2,2,2); maximum lag order = 2.

4.3 Bounds test for cointegration

Given the selected specification, the bounds F-test is applied to examine whether a long-run relationship exists among the variables (Table 5). The computed F-statistic (5.395) exceeds the upper critical bound at all conventional significance levels, including the 1% level (5.06). The null hypothesis of no cointegration is therefore rejected, which supports H1: CO_2 emissions, renewable energy consumption, economic growth, FDI and trade openness share a long-run equilibrium relationship in Algeria. Because the critical values reported are those tabulated by Pesaran et al. (2001) and the sample is small, this conclusion should be read with the caveat that small-sample bounds are generally more demanding (Narayan, 2005); the margin by which the statistic exceeds the upper bound at the 1% level nevertheless provides reasonable comfort.

Table 5. ARDL bounds test for cointegration

Test statistic	Value	Significance level	Lower bound I(0)	Upper bound I(1)	Decision
F-bounds statistic	**5.395**	10%	2.45	3.52	Cointegration
		5%	2.86	4.01	
		2.5%	3.25	4.49	
		1%	3.74	5.06	

Source: Authors' estimations using R. Critical values: Pesaran et al. (2001), case III (unrestricted intercept, no trend), k = 4.

4.4 Short-run dynamics and the error-correction mechanism

Table 6 reports the UECM estimates. The coefficient on the lagged dependent variable, $\ln CO_2(-1)$, is the error-correction term; terms in levels dated $t-1$ form the long-run component of the model, while terms prefixed by Δ capture short-run dynamics.

Table 6. Unrestricted error-correction model (UECM): short-run estimates

Variable	Coefficient	Std. error	t-statistic	p-value	Significance
Constant	−0.0012	0.6980	−0.0018	0.9986	Not significant
$\ln CO_2(-1)$ (error-correction term)	**−0.4745**	0.1411	−3.3624	**0.0033**	1%
$\ln REC(-1)$	0.0317	0.0153	2.0728	0.0520	10%
$\ln GDP(-1)$	0.0509	0.0448	1.1379	0.2693	Not significant
$\ln FDI(-1)$	−0.0093	0.0127	−0.7327	0.4727	Not significant
$\ln OPEN(-1)$	−0.2124	0.1250	−1.6987	0.1057	Not significant
$\Delta \ln REC$	0.0126	0.0127	0.9958	0.3318	Not significant
$\Delta \ln GDP$	−0.4055	0.2951	−1.3742	0.1854	Not significant
$\Delta \ln GDP(-1)$	−0.3636	0.2899	−1.2542	0.2250	Not significant
$\Delta \ln FDI$	0.0135	0.0103	1.3128	0.2049	Not significant
$\Delta \ln FDI(-1)$	**0.0246**	0.0084	2.9095	**0.0090**	1%
$\Delta \ln OPEN$	−0.0177	0.0833	−0.2123	0.8341	Not significant

Table 6. Unrestricted error-correction model (UECM): short-run estimates *(continued)*

Variable	Coefficient	Std. error	t-statistic	p-value	Significance
ΔlnOPEN(−1)	**0.1565**	0.0796	1.9649	**0.0642**	10%

Source: Authors' estimations using R. Note: coefficients significant at the 10% level or better are shown in bold where they relate to the error-correction term and to short-run differences.

The error-correction coefficient equals −0.4745, carries the expected negative sign and is statistically significant at the 1% level (t = −3.362, p = 0.003). It implies that about 47.5% of any deviation of emissions from their long-run equilibrium is eliminated within one year, so that full convergence takes roughly two years (1/0.4745 ≈ 2.1) and the half-life of a shock is about 1.1 years. The adjustment speed is therefore moderate, in line with the persistence of the capital stock and the gradual nature of structural change in energy systems. The negative and significant error-correction term also corroborates the cointegration evidence of the bounds test.

Among the short-run dynamics, the first lag of the change in FDI has a positive and statistically significant coefficient (0.0246; p = 0.009), and the first lag of the change in trade openness is positive and significant at the 10% level (0.1565; p = 0.064). These results are consistent with a transitional, short-lived emission-increasing effect of capital inflows and trade expansion, as new investment and trade flows raise industrial activity, transport and freight before efficiency gains materialise. The contemporaneous changes in renewable energy consumption, GDP, FDI and openness are statistically insignificant, as is the first lag of ΔlnGDP, although the sign of the contemporaneous output effect (−0.4055) is negative. The lagged level of lnREC enters with a positive coefficient (0.0317) that is marginally significant at the 10% level (p = 0.052); because this term belongs to the long-run component of the UECM, it is best interpreted together with the long-run multiplier discussed below. The lagged levels of lnGDP, lnFDI and lnOPEN are not significant at conventional levels (p = 0.269, 0.473 and 0.106, respectively).

4.5 Long-run elasticities

Table 7 reports the long-run elasticities derived from the estimated model. Because the specification is log-log, each coefficient gives the percentage change in CO_2 emissions associated with a 1% change in the corresponding regressor, other things equal.

Table 7. Long-run elasticities of the ARDL model

Variable	Coefficient	Interpretation
lnREC	+0.0934	Early transitional stage of the energy system and initial efforts to integrate clean energy
lnGDP	−1.5134	Onset of decoupling between economic growth and emissions
lnFDI	+0.0606	Inflows directed to conventional, energy-intensive activities
lnOPEN	−0.1551	Trade contributes to environmental efficiency and clean-technology transfer

Source: Authors' estimations using R. Dependent variable: $\ln CO_2$. Coefficients are long-run multipliers and are reported as point estimates.

The output elasticity is negative and large (−1.5134): in the long run, a 1% increase in real GDP is associated with a 1.51% reduction in emissions. The sign is consistent with H3 and with the onset of decoupling, but the magnitude exceeds what is commonly reported in the literature and may partly capture omitted trending factors such as improvements in energy efficiency and structural change; it should be read as indicative rather than precise, especially given the short sample.

The elasticity of renewable energy consumption is small and positive (+0.0934). This does not support the expectation of a negative sign under H2, but it is consistent with the early-transition interpretation advanced in Section 2.2: with a renewable share that remains modest relative to a gas-dominated system, additional renewable consumption has not yet displaced enough fossil energy to lower aggregate emissions, and the emissions embodied in deployment may offset part of the benefit. The marginally significant positive level term in Table 6 points in the same direction.

FDI carries a small positive elasticity (+0.0606), in line with the pollution haven channel and with the positive short-run effect of lagged FDI changes, suggesting that inflows have so far been oriented towards conventional, energy-intensive activities (H4). Trade openness, by contrast, has a negative elasticity (−0.1551), supporting H5: in the long run, openness is associated with lower emissions, plausibly through the import of more efficient equipment and the diffusion of cleaner techniques, even though short-run effects are positive.

4.6 Diagnostic and stability tests

The reliability of the estimates depends on the residuals satisfying the classical assumptions and on the stability of the parameters over the sample period. Table 8 summarises the diagnostic tests.

Table 8. Residual diagnostic tests

Test	Null hypothesis	Statistic	p-value	Decision
Breusch–Godfrey	No serial correlation	0.1226	0.7263	Not rejected
Breusch–Pagan	Homoskedasticity	15.3935	0.2206	Not rejected
Jarque–Bera	Normally distributed residuals	0.8667	0.6483	Not rejected

Source: Authors' estimations using R.

None of the three tests rejects its null hypothesis at the 5% level: the residuals show no evidence of serial correlation (p = 0.726), heteroskedasticity (p = 0.221) or departure from normality (p = 0.648). Parameter stability was assessed with the OLS-CUSUM test and the recursive-estimates (RE) fluctuation test. As Figure 1 shows, the empirical fluctuation processes remain within the 5% critical boundaries throughout the sample, so there is no evidence of structural instability in the estimated model.

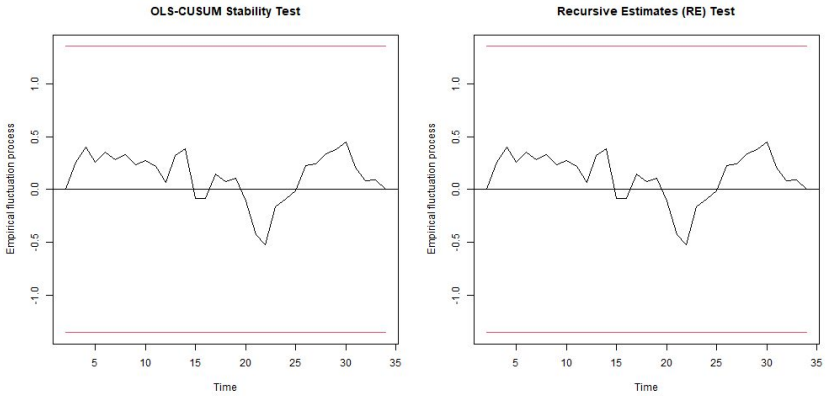


Figure 1. Parameter stability tests: OLS-CUSUM (left) and recursive-estimates fluctuation test (right)

Source: Authors' estimations using R. Red lines denote the 5% critical boundaries.

5. DISCUSSION

The results paint a coherent but nuanced picture. First, the existence of a cointegrating relationship, together with an error-correction term implying a half-life of roughly one year, indicates that emissions in Algeria are tied to the macroeconomic variables examined and that deviations from the long-run path are corrected within a couple of years. Policy shocks that alter renewable deployment, investment or trade patterns can therefore be expected to feed through to emissions over a medium-term horizon.

Second, the negative long-run output elasticity is encouraging but must be interpreted with care. It is consistent with relative or even absolute decoupling in the sample period, yet the literature warns that decoupling is neither automatic nor sufficient (Stern, 2004; Haberl et al., 2020; Parrique et al., 2019). It also contrasts with Bouznit and Pablo-Romero (2016), who find that the EKC turning point for Algeria lies at a very high income level; the difference may reflect the longer and more recent sample used here, the inclusion of renewable energy, FDI and openness as controls, or both. In a hydrocarbon-dependent economy, output fluctuates with energy prices and export volumes, so the elasticity may reflect cyclical and compositional movements as much as a durable technological shift. The estimate is better treated as a signal that structural change is under way than as a

guarantee that growth can proceed without further decarbonisation effort.

Third, the positive renewable-energy coefficient contrasts with studies that find mitigating effects (Bilgili et al., 2016; Dogan & Seker, 2016), including the study of Belaïd and Youssef (2017) for Algeria, who report a beneficial effect of renewable electricity consumption. A plausible reconciliation is that the panel studies examine economies with much larger renewable shares and more mature grids, whereas Algeria's renewable consumption has so far been too limited to displace fossil generation at scale; differences in the sample period (1980–2012 in Belaïd and Youssef) and in the measure used (renewable electricity versus the renewable share of total energy) may also matter, and the discrepancy warrants further investigation. This finding is directly relevant for the hydrogen agenda: electrolysis requires large quantities of electricity, and if it were supplied by the existing gas-based system, producing "green" hydrogen would, in effect, increase emissions. Green hydrogen projects should therefore be conditioned on the addition of new renewable capacity rather than on the diversion of existing supply, and the national renewable programme should be viewed as a prerequisite rather than a parallel track.

Fourth, the signs of FDI and trade openness underline the role of the external sector as a channel for either carbon lock-in or low-carbon transformation. The positive FDI effect is consistent with the pollution haven channel and contrasts with the mitigating effects reported by Al-mulali and Tang (2013) for the GCC countries and by Zhang and Zhou (2016) for Chinese regions, a difference that may reflect the sectoral concentration of FDI in Algeria. The negative openness elasticity accords with Frankel and Rose (2005) but differs from the adverse effects that Managi et al. (2009) report for non-OECD countries, suggesting that, in Algeria's case, technology imports may have outweighed scale and composition effects in the long run. Both channels are likely to matter for hydrogen, since electrolysers, renewable equipment and export-market access depend on trade and foreign capital.

6. CONCLUSION, POLICY IMPLICATIONS AND LIMITATIONS

6.1 Main findings

This study analysed the effects of renewable energy consumption, economic growth, FDI and trade openness on CO_2 emissions in Algeria over 1990–2023 using an ARDL(1,1,2,2,2) model. The bounds test ($F = 5.395$) establishes a long-run equilibrium relationship, and the error-correction coefficient (−0.4745) shows that about 47.5% of disequilibrium is corrected each year. In the long run, output (−1.5134) and trade openness (−0.1551) are negatively associated with emissions, while renewable energy consumption (+0.0934) and FDI (+0.0606) are positively associated with them. Diagnostic and stability tests support the adequacy of the model. Taken together, the results indicate that the Algerian economy has begun to decouple emissions from growth, but that its renewable energy and investment profile is not yet sufficient to deliver the emission reductions that a green hydrogen economy would require.

6.2 Policy implications

Scale up renewable capacity ahead of, and in addition to, hydrogen projects. Hydrogen electrolysis should be supplied by newly installed renewable capacity, supported by investment in grid flexibility and storage. Accelerating the national renewable programme is a precondition for the climate credentials of green hydrogen.

Align FDI incentives with low-carbon sectors. Tax and customs advantages should be reserved for investments in renewable energy, energy efficiency and low-emission industries, accompanied by environmental screening of inflows to limit pollution-haven effects.

Use trade policy to facilitate clean-technology imports. Lowering barriers to high-efficiency capital goods and renewable equipment, while aligning product standards with those of export markets such as the European Union (including its Carbon Border Adjustment Mechanism), would reinforce the favourable long-run effect of openness.

Continue structural diversification. Strengthening non-hydrocarbon sectors with low carbon intensity would consolidate the decoupling signalled by the output elasticity and reduce exposure to fossil-fuel cycles.

6.3 Limitations and future research

Several limitations qualify the findings. First, the sample is short (34 observations) relative to the number of parameters of the ARDL(1,1,2,2,2) specification, and the critical bounds used are asymptotic. Second, unit-root evidence rests on ADF tests alone; the first-difference result for lnFDI is not conclusive, and tests that allow for

structural breaks (for example, around the 2008 financial crisis, the 2014 oil-price collapse and the COVID-19 shock) would strengthen the analysis. Third, the model omits other determinants of emissions, such as non-renewable energy use, energy intensity, financial development and institutional quality. Fourth, the long-run multipliers are reported as point estimates; formal inference on them, for instance through the delta method or bootstrap procedures, would further strengthen the evidence. Fifth, the link to green hydrogen is interpretive: the model does not include hydrogen-related variables, and causal conclusions should be drawn with caution. Future research could employ asymmetric (NARDL) or Fourier-based ARDL specifications, include energy-mix and institutional variables, and, as data become available, examine sector-level effects of hydrogen-related investment.

REFERENCES

Akaike, H. (1974). A new look at the statistical model identification. *IEEE Transactions on Automatic Control, 19*(6), 716–723. https://doi.org/10.1109/TAC.1974.1100705

Algeria Invest. (2026, March 11). Du Sahara à l'Europe : la stratégie solaire de l'Algérie. https://algeriainvest.com/premium-news/du-sahara-a-leurope-la-strategie-solaire-de-lalgerie

Al-mulali, U., & Tang, C. F. (2013). Investigating the validity of pollution haven hypothesis in the Gulf Cooperation Council (GCC) countries. *Energy Policy, 60*, 813–819. https://doi.org/10.1016/j.enpol.2013.05.055

Antweiler, W., Copeland, B. R., & Taylor, M. S. (2001). Is free trade good for the environment? *American Economic Review, 91*(4), 877–908. https://doi.org/10.1257/aer.91.4.877

Apergis, N., & Payne, J. E. (2010). Renewable energy consumption and economic growth: Evidence from a panel of OECD countries. *Energy Policy, 38*(1), 656–660. https://doi.org/10.1016/j.enpol.2009.09.002

Belaïd, F., & Youssef, M. (2017). Environmental degradation, renewable and non-renewable electricity consumption, and economic growth: Assessing the evidence from Algeria. *Energy Policy, 102*, 277–287. https://doi.org/10.1016/j.enpol.2016.12.012

Bilgili, F., Koçak, E., & Bulut, Ü. (2016). The dynamic impact of renewable energy consumption on CO_2 emissions: A revisited Environmental Kuznets Curve approach. *Renewable and Sustainable Energy Reviews, 54*, 838–845. https://doi.org/10.1016/j.rser.2015.10.080

Birdsall, N., & Wheeler, D. (1993). Trade policy and industrial pollution in Latin America: Where are the pollution havens? *Journal of Environment & Development, 2*(1), 137–149. https://doi.org/10.1177/107049659300200107

Bouznit, M., & Pablo-Romero, M. del P. (2016). CO_2 emission and economic growth in Algeria. *Energy Policy, 96*, 93–104. https://doi.org/10.1016/j.enpol.2016.05.036

Breusch, T. S. (1978). Testing for autocorrelation in dynamic linear models. *Australian Economic Papers, 17*(31), 334–355. https://doi.org/10.1111/j.1467-8454.1978.tb00635.x

Breusch, T. S., & Pagan, A. R. (1979). A simple test for heteroscedasticity and random coefficient variation. *Econometrica, 47*(5), 1287–1294. https://doi.org/10.2307/1911963

Brown, R. L., Durbin, J., & Evans, J. M. (1975). Techniques for testing the constancy of regression relationships over time. *Journal of the Royal Statistical Society: Series B, 37*(2), 149–192. https://doi.org/10.1111/j.2517-6161.1975.tb01532.x

Copeland, B. R., & Taylor, M. S. (1994). North–South trade and the environment. *Quarterly Journal of Economics, 109*(3), 755–787. https://doi.org/10.2307/2118421

Copeland, B. R., & Taylor, M. S. (2004). Trade, growth, and the environment. *Journal of Economic Literature, 42*(1), 7–71. https://doi.org/10.1257/002205104773558047

Dickey, D. A., & Fuller, W. A. (1979). Distribution of the estimators for autoregressive time series with a unit root. *Journal of the American Statistical Association, 74*(366), 427–431. https://doi.org/10.1080/01621459.1979.10482531

Dogan, E., & Seker, F. (2016). The influence of real output, renewable and non-renewable energy, trade and financial development on carbon emissions in the top renewable energy countries. *Renewable and Sustainable Energy Reviews, 60*, 1074–1085. https://doi.org/10.1016/j.rser.2016.02.006

Ehrlich, P. R., & Holdren, J. P. (1971). Impact of population growth. *Science, 171*(3977), 1212–1217. https://doi.org/10.1126/science.171.3977.1212

Frankel, J. A., & Rose, A. K. (2005). Is trade good or bad for the environment? Sorting out the causality. *Review of Economics and Statistics, 87*(1), 85–91. https://doi.org/10.1162/0034653053327577

Godfrey, L. G. (1978). Testing against general autoregressive and moving average error models when the regressors include lagged dependent variables. *Econometrica, 46*(6), 1293–1301. https://doi.org/10.2307/1913829

Green Hydrogen Organisation. (n.d.). *GH2 country portal: Algeria*. https://gh2.org/countries/algeria

Grossman, G. M., & Krueger, A. B. (1995). Economic growth and the environment. *Quarterly Journal of Economics, 110*(2), 353–377. https://doi.org/10.2307/2118443

Haberl, H., Wiedenhofer, D., Virág, D., Kalt, G., Plank, B., Brockway, P., … Creutzig, F. (2020). A systematic review of the evidence on decoupling of GDP, resource use and GHG emissions, part II: Synthesizing the insights. *Environmental Research Letters, 15*(6), 065003. https://doi.org/10.1088/1748-9326/ab842a

Intergovernmental Panel on Climate Change. (2021). *Climate change 2021: The physical science basis. Contribution of Working Group I to the Sixth Assessment Report*. Cambridge University Press. https://doi.org/10.1017/9781009157896

International Energy Agency. (2019). *The future of hydrogen: Seizing today's opportunities*. IEA Publications.

International Renewable Energy Agency. (2022). *Geopolitics of the energy transformation: The hydrogen factor*. IRENA.

Jarque, C. M., & Bera, A. K. (1987). A test for normality of observations and regression residuals. *International Statistical Review, 55*(2), 163–172. https://doi.org/10.2307/1403192

Managi, S., Hibiki, A., & Tsurumi, T. (2009). Does trade openness improve environmental quality? *Journal of Environmental Economics and Management, 58*(3), 346–363. https://doi.org/10.1016/j.jeem.2009.04.008

Ministry of Energy and Mines (Algeria). (2023). *Algerian national hydrogen development strategy: Roadmap*. Algiers.

Narayan, P. K. (2005). The saving and investment nexus for China: Evidence from cointegration tests. *Applied Economics, 37*(17), 1979–1990. https://doi.org/10.1080/00036840500278103

Nordhaus, W. D. (2008). *A question of balance: Weighing the options on global warming policies*. Yale University Press.

Omri, A., Nguyen, D. K., & Rault, C. (2014). Causal interactions between CO_2 emissions, FDI, and economic growth: Evidence from dynamic simultaneous-equation models. *Economic Modelling, 42*, 382–389. https://doi.org/10.1016/j.econmod.2014.07.026

Organisation for Economic Co-operation and Development. (2002). *Indicators to measure decoupling of environmental pressure from economic growth* (SG/SD(2002)1/FINAL). OECD.

Panayotou, T. (1997). Demystifying the environmental Kuznets curve: Turning a black box into a policy tool. *Environment and Development Economics, 2*(4), 465–484. https://doi.org/10.1017/S1355770X97000211

Parrique, T., Barth, J., Briens, F., Kerschner, C., Kraus-Polk, A., Kuokkanen, A., & Spangenberg, J. H. (2019). *Decoupling debunked: Evidence and arguments against green growth as a sole strategy for sustainability*. European Environmental Bureau.

Pesaran, M. H., & Shin, Y. (1999). An autoregressive distributed-lag modelling approach to cointegration analysis. In S. Strøm (Ed.), *Econometrics and economic theory in the 20th century: The Ragnar Frisch Centennial Symposium* (pp. 371–413). Cambridge University Press. https://

doi.org/10.1017/CCOL521633230.011

Pesaran, M. H., Shin, Y., & Smith, R. J. (2001). Bounds testing approaches to the analysis of level relationships. *Journal of Applied Econometrics, 16*(3), 289–326. https://doi.org/10.1002/jae.616

Sadorsky, P. (2009). Renewable energy consumption and income in emerging economies. *Energy Policy, 37*(10), 4021–4028. https://doi.org/10.1016/j.enpol.2009.05.003

Stern, D. I. (2004). The rise and fall of the environmental Kuznets curve. *World Development, 32*(8), 1419–1439. https://doi.org/10.1016/j.worlddev.2004.03.004

Stern, N. (2006). *Stern review on the economics of climate change*. HM Treasury.

United Nations Environment Programme. (2011). *Towards a green economy: Pathways to sustainable development and poverty eradication*. UNEP.

York, R., Rosa, E. A., & Dietz, T. (2003). STIRPAT, IPAT and ImPACT: Analytic tools for unpacking the driving forces of environmental impacts. *Ecological Economics, 46*(3), 351–365. https://doi.org/10.1016/S0921-8009(03)00188-5

Zhang, C., & Zhou, X. (2016). Does foreign direct investment lead to lower CO_2 emissions? Evidence from a regional analysis in China. *Renewable and Sustainable Energy Reviews, 58*, 943–951. https://doi.org/10.1016/j.rser.2015.12.226