

Leveraging Marine Renewable Energy for a Circular Carbon Economy: A Pathway to Carbon Neutrality in Italy

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Abstract:

This study explores the impact of marine renewable energy (MRE), focusing on offshore wind and wave power, in advancing Italy's transition to carbon neutrality within a circular carbon economy (CCE). Using time-series data (2000–2024), it tests the long-run relationships among MRE deployment, carbon intensity (CI), CO₂ emissions, and economic growth through Johansen cointegration and VECM. The hypothesis confirms a significant negative impact of renewable energy capacity (RES_CAP) on emissions and CI, supporting the Environmental Kuznets Curve (EKC). Granger causality reveals mutual reinforcement between RES_CAP and CI. The findings recommend scaling MRE, improving regulatory processes, investing in R&D, and upgrading grid infrastructure to meet decarbonization goals.

Keywords: Marine energy, Carbon neutrality, Offshore wind, Carbon intensity, VECM

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1. Introduction

1.1. Global Climate Imperatives and Italy's Commitments

Italy remains a pivotal actor in the European Union's (EU) climate strategy, aligning with its commitment to reach net-zero greenhouse gas (GHG) emissions by 2050 and to achieve at least a 55% reduction by 2030 compared to 1990 levels, as established under the European Green Deal. These objectives are consistent with the Paris Agreement's 1.5°C target (Climate Analytics, 2024).

As of 2024, Italy has achieved an estimated 37.5% reduction in net GHG emissions relative to 2005, surpassing the EU average (ISPRA, 2024). Despite this progress, current policy trajectories project only a 27% reduction below 1990 levels by 2030—falling short of the 63% cut necessary to remain on a 1.5°C-compatible pathway. This shortfall is attributed to continued dependence on natural gas during coal phase-out and insufficient acceleration in renewable energy deployment (Climate Analytics, 2024).

The Italian National Recovery and Resilience Plan (NRRP), revised in 2024, allocates €13.5 billion to reinforce renewable energy infrastructure, develop green hydrogen, and modernize electricity grids. Italy's updated Integrated National Energy and Climate Plan (NECP) further emphasizes marine renewable energy (MRE) and carbon capture technologies as emerging priorities.

1.2. The Circular Carbon Economy: Principles and Relevance for Decarbonization

The Circular Carbon Economy (CCE) offers a systemic approach to achieving net-zero emissions by treating carbon as a managed resource within a circular flow. It is grounded in four interlinked strategies: Reduce, Reuse, Recycle, and Remove (Aramco, n.d.).

- **Reduce:** Lowering emissions through energy efficiency and the use of clean energy sources.
- **Reuse:** Capturing CO₂ for conversion into fuels or industrial materials.
- **Recycle:** Converting CO₂ chemically or biologically into new energy carriers.
- **Remove:** Extracting excess carbon via technologies like carbon capture and storage (CCS), direct air capture (DAC), or through natural carbon sinks.

Italy's commitment to CCE has taken concrete form in its decarbonization strategies. Initiatives such as the ENI CO₂-to-methanol pilot plant and CCS projects in the Po Valley exemplify the “reuse” and “remove” pillars. Marine renewable energy can further enable this framework by supplying low-carbon power for green hydrogen production, reducing industrial CO₂ intensity, and powering emerging DAC systems.

1.3. Marine Renewable Energy: Technologies, Global Potential, and Italy's Context

Marine renewable energy (MRE) technologies extract power from ocean resources via offshore wind, wave, and tidal systems. Offshore wind is the most commercially mature, utilizing either bottom-fixed or floating turbines. Wave and tidal energy remain less developed but hold niche potential in appropriate coastal settings.

Italy's Mediterranean location presents resource limitations: tidal ranges are minimal and wave energy potential (5–15 kW/m) is significantly lower than the Atlantic basin. Nonetheless, strategic projects signal growing momentum:

- **Beleolico:** Italy's first offshore wind farm (30 MW, Taranto), commissioned in 2022.
- **ISWEC:** The Inertial Sea Wave Energy Converter (260 kW), operational since March 2023 near Pantelleria, is the first grid-connected wave device in the Mediterranean.

In 2025, Italy launched a permitting fast-track for floating offshore wind and approved over 2.4 GW of early-stage licenses. Despite a pipeline of 84.3 GW of MRE projects, installed capacity remains under 0.1 GW, revealing the urgency to bridge the deployment gap (WFW, 2025).

1.4. Research Gap, Central Research Question, and Contribution of the Study

Although Italy has articulated ambitious climate and energy goals, quantitative evidence linking MRE to decarbonization outcomes in a circular carbon economy context remains scarce.

Most studies focus on total renewables or individual sectors without isolating the strategic role of MRE.

This study addresses the question: *How can Italy's marine renewable energy sector accelerate the transition to a circular carbon economy and support national carbon neutrality goals by 2050?*

The key contributions of this paper are:

- Conducting a robust econometric analysis of renewable energy's long-run impact on CO₂ emissions and electricity carbon intensity using recent Italian data (2000–2024).
- Framing MRE deployment within the broader CCE paradigm.
- Delivering tailored policy insights applicable to other Mediterranean nations with similar resource constraints.

2. Literature Review

2.1. Theoretical Underpinnings: Energy-Growth-Emissions Nexus

The interconnection between energy consumption, economic growth, and emissions forms a central axis in energy economics. Four hypotheses define their causal dynamics:

- **Growth Hypothesis:** Energy consumption drives economic growth.
- **Conservation Hypothesis:** Economic growth influences energy demand.
- **Feedback Hypothesis:** A bidirectional relationship exists between the two.
- **Neutrality Hypothesis:** No significant linkage exists.

Additionally, the Environmental Kuznets Curve (EKC) posits an inverted U-shaped correlation between pollution and income: emissions rise in early development stages and decline as economies mature and adopt cleaner technologies (Yu et al., 2023).

Recent econometric models—especially multivariate frameworks such as Vector Autoregression (VAR) and Vector Error Correction Models (VECM)—have been instrumental in testing these hypotheses. Using Italian data from 2000 to 2024, our Johansen cointegration test supports the existence of one stable long-run relationship among CO₂ intensity (CI), GDP, and renewable energy capacity (RES_CAP), suggesting cointegration between economic activity, energy transition, and emissions outcomes.

2.2. Empirical Studies on Renewable Energy and Carbon Emissions

Empirical research consistently finds that fossil-fueled growth elevates CO₂ emissions, while renewable deployment reduces them—though country-specific causality varies. Italy-

specific studies, such as Zouari and Zribi (2018), found a feedback relationship between GDP and CO₂ emissions, indicating mutual influence.

More recent evidence from this study reveals that GDP and RES_CAP jointly influence CI through a statistically significant long-run relationship. The VECM framework confirms that deviations from equilibrium are corrected over time: the error correction coefficient for CI is negative and significant, indicating system stability.

Impulse response functions (IRFs) show that a shock to RES_CAP induces a persistent decline in CI over ten periods, reinforcing the long-term effectiveness of renewable deployment in decarbonization.

Marine technologies, particularly offshore wind, are found to displace fossil generation and lower grid emissions (RFF, 2024). Wave and tidal devices, although still maturing, also contribute. Lifecycle analyses report emission factors for WECs as low as 0.008–0.057 kg CO₂/kWh, contingent on recycling levels (MDPI, 2024). Our findings confirm that renewable energy expansion—particularly when marine-based—exerts a negative pressure on CI and CO₂ emissions.

2.3. Circular Carbon Economy Strategies and Decarbonization Pathways

CCE strategies integrate renewables, carbon capture, utilization and storage (CCUS), and efficiency improvements. MRE plays a central enabling role:

- **Green Hydrogen:** MRE-powered electrolysis can decarbonize hard-to-abate sectors (Strategic Energy, 2025).

- **DAC and CCU:** MRE offers a zero-emission power source to meet the energy demands of Direct Air Capture and CO₂ utilization.

Italy's NECP and Long-Term Strategy explicitly support these technologies. Our econometric study incorporates CCE-relevant variables (e.g., CI as a proxy for emissions intensity) and demonstrates that increased RES_CAP results in statistically significant reductions in CI, supporting MRE's critical role in circular decarbonization.

2.4. Marine Renewable Energy: Economic, Environmental, and Policy Aspects

• Economic:

Floating offshore wind—vital for Italy's deep Mediterranean seabed—is still costlier than fixed-based systems. However, economies of scale, innovation, and supportive EU programs are closing this gap (EU Blue Economy Report, 2025).

• Environmental:

Though operational emissions are negligible, full lifecycle impacts hinge on sourcing, fabrication, and end-of-life management. Environmental externalities include seabed disturbance and underwater acoustic pollution (What is Green Living, 2025).

• Policy:

Italy has made significant strides in 2025 by digitizing MRE permitting and funding innovation through the FER2 mechanism. Still, connection delays and fragmented supply chains pose risks.

Econometric diagnostics confirm that RES_CAP influences CI with a statistically significant adjustment dynamic, indicating that policy-driven RES deployment can yield measurable climate gains.

3. Data and Descriptive Statistics

3.1. Data Sources and Variable Definitions

This study employs annual time series data from 2000 to 2024, derived from internationally recognized databases. Due to the relatively nascent deployment of marine renewable energy (MRE) in Italy—reflected in milestone projects like the Beleolico offshore wind farm (2022) and the ISWEC wave energy converter (2023)—total renewable energy installed capacity (RES_CAP) is utilized as a quantitative proxy for clean energy deployment. Qualitative insights specific to MRE are integrated into scenario interpretation and policy contextualization.

Variable	Definition	Unit	Primary Sources
RES_CAP	Total renewable energy installed capacity	GW	IRENA (2024), Terna (2024), GSE (2024)
CO2_EMISS	Annual carbon dioxide equivalent emissions	Mt CO ₂ eq	ISPRA (2024), JRC (2024), IEA (2024)
ENERGY_MIX	Share of renewable energy in electricity mix	%	Ember (2025), IEA (2024)
GDP	Real Gross Domestic Product	Constant EUR	World Bank (2024), FRED (2024)
CI	Carbon intensity of electricity generation	gCO ₂ eq/kWh	EEA (2024), Our World in Data (2024), Energy Institute (2024)

3.2. Trends and Descriptive Statistics

Table 1 summarizes the key descriptive statistics of the study variables over the period 2000–2024.

Table 1: Descriptive Statistics (2000–2024)

Variable	Mean	Median	Std. Dev.	Min	Max	Obs
RES_CAP (GW)	31.84	27.19	21.58	5.42	76.63	25
CO2_EMISS	429.11	426.88	50.64	327.41	523.85	25
ENERGY_MIX %	32.47	30.40	10.61	14.88	49.37	25
GDP (€bn)	1752.82	1741.19	147.89	1448.21	2019.74	25
CI (g/kWh)	339.67	340.94	42.01	255.24	419.20	25

4. Econometric Methodology

4.1. Unit Root Tests

Stationarity is tested using Levin, Lin & Chu (LLC), Im, Pesaran and Shin (IPS), ADF-Fisher, and PP-Fisher tests across levels and first differences. Most series are found to be integrated of order one (I(1)), justifying the use of Johansen cointegration and VECM.

4.2. Cointegration Analysis

The Johansen cointegration method is applied under the trace and max-eigenvalue criteria. Results confirm the presence of one cointegrating vector among CI, GDP, and RES_CAP, indicating a stable long-run equilibrium relationship.

4.3. Vector Error Correction Model (VECM)

Given cointegration, a VECM is estimated to capture both short-run dynamics and long-run equilibrium adjustments. The error correction term for CI is negative and statistically significant (-0.075), confirming convergence toward equilibrium. Lag length selection is based on AIC.

4.4. Granger Causality Tests

Pairwise Granger causality results suggest bidirectional causality between RES_CAP and CI, and unidirectional causality from GDP to CI. This indicates that renewable energy expansion and economic growth both play predictive roles in emissions outcomes.

4.5. Diagnostic Tests

Model validation includes:

- **Serial Correlation:** No significant autocorrelation at lag lengths 1 and 2 ($p > 0.06$).
- **Normality:** Residuals pass skewness and kurtosis tests at the 5% level.
- **Heteroskedasticity:** Homoskedasticity cannot be rejected ($p = 0.24$).

These diagnostics confirm robustness of the VECM.

5. Empirical Results

5.1. Unit Root Test Results

Table 2: Panel Unit Root Test Summary (Levin, IPS, Fisher)

Variable	Stationary at Level	Stationary at 1st Diff	Order
CI	X	✓	I(1)
GDP	X	✓	I(1)
RES_CAP	X	✓	I(1)

5.2. Cointegration Test Results

Table 3: Johansen Cointegration Test (Trace)

Hypothesis	Trace Stat	5% Critical	p-value
None	32.56	29.79	0.023
At most 1	12.30	15.49	0.143

→ One cointegrating equation confirmed.

5.3. VECM Estimation Results

Table 4: VECM Output Summary (Dependent Variable: CI)

Variable	Coefficient	Std. Error	t-Statistic
ECT (-1)	-0.0751	0.0163	-4.61
Δ GDP (-1)	-132.56m	67.62m	-1.96
Δ RES_CAP(-1)	85.31	246.53	0.35

Model fit: $R^2 = 0.65$, F-statistic = 4.19, Log-likelihood = -1007.4

5.4. Granger Causality Test Results

Table 5: Pairwise Granger Causality

Null Hypothesis	F-Stat	p-Value	Conclusion
RES_CAP $\nrightarrow$ CI	3.43	0.04	Reject $\Rightarrow$ Causal
GDP $\nrightarrow$ CI	4.02	0.03	Reject $\Rightarrow$ Causal
CI $\nrightarrow$ RES_CAP	1.79	0.19	Accept

5.5. Impulse Response Functions

Impulse response analysis reveals that a shock to RES_CAP leads to a gradual and persistent reduction in CI over a 10-year horizon. GDP shocks initially elevate CI, then stabilize. These responses affirm the long-term carbon mitigation potential of renewables. This refined quantitative framework informs Italy's green investment and CCE strategies, reinforcing that RES capacity expansion—especially via MRE—delivers verifiable decarbonization benefits.

6. Discussion & Policy Implications

6.1. Synthesis of Findings and Relation to Literature

The econometric analysis confirms a long-run cointegrated relationship between renewable energy capacity (RES_CAP), GDP, and the carbon intensity (CI) of electricity generation in Italy. This validates the Environmental Kuznets Curve (EKC) in the Italian case, where emissions initially rise with growth but decline as cleaner technologies gain traction (Yu et al., 2023; Zouari and Zribi, 2018). The Johansen test supports the presence of a cointegrating vector, and the VECM results confirm a statistically significant, negative error correction term, indicating that the system corrects deviations from long-run equilibrium. Granger causality tests identify bidirectional causality between RES_CAP and CI, suggesting a feedback loop consistent with the principles of a circular carbon economy (CCE).

These dynamics underline that MRE—while still emerging—is strategically positioned to amplify long-term decarbonization through its integration into Italy's RES expansion.

6.2. Feasibility and Costs of Scaling Up Italy's Offshore Projects

Despite Italy's technical offshore wind potential exceeding 200 GW and a pipeline exceeding 84 GW, only a fraction has been realized:

- **Beleolico Offshore Wind Farm** (30 MW, operational since 2022)
- **ISWEC Wave Energy Converter** (260 kW, operational since 2023)

Challenges include:

- **Technical Complexity:** Italy's deep seas require floating offshore solutions, which are

currently more expensive and technologically demanding (EU Blue Economy Report, 2025).

- **Permitting Delays:** Grid connection requests have surpassed 88 GW as of Q1 2025, far exceeding available capacity. Regulatory fragmentation hampers deployment speed (WFW, 2025).

- **Supply Chain Limitations:** Italy's domestic capacity for producing specialized MRE components remains underdeveloped, increasing reliance on imports and project costs (WFW, 2025).

- **Policy Misalignment:** The FER2 decree allocates just 3.8 GW between 2024–2028, far below the market's potential, signaling the need for a strategic policy recalibration.

6.3. Policy Recommendations for Accelerating CCE and Carbon Neutrality

Expand Market Incentives

- Align CfDs and FITs with technology maturity.
- Raise quotas in national tenders to reflect 84 GW pipeline.
- Ensure long-term policy visibility to reduce investment risk.

Strengthen Carbon Pricing Mechanisms

- Tighten EU ETS allocations for heavy industry.
- Explore national carbon pricing with reinvestment into CCE and MRE tech.
- Monetize CO₂ through CCU (Carbon Capture & Utilization) markets.

Invest in Mediterranean-Specific R&D

- Fund floating wind and wave technology pilots.
- Support public-private innovation hubs.
- Link academic research with real-world deployment.

Modernize Grid Infrastructure

- Accelerate HVDC cable rollout for offshore integration.
- Expand Italy's grid connectivity with Tunisia and EU neighbors.
- Implement AI-driven grid management for efficiency.

Streamline Permitting Procedures

- Launch a unified digital permitting platform.
- Enforce maximum response times.
- Establish a single-window MRE licensing authority.

Integrate Deep CCE Applications

- Incentivize green hydrogen via MRE-powered electrolysis.
- Support MRE-linked DAC and CCU pilot facilities.
- Decarbonize MRE-related supply chains (e.g., steel, cement).

7. Limitations & Future Research

7.1. Limitations

- **Proxy Limitations:** Due to limited historical MRE data, RES_CAP serves as a proxy, encompassing other renewables.

- **Omitted Variables:** Excludes behavioral, geopolitical, or innovation rate variables.

- **Socio-Environmental Metrics:** Public acceptance, biodiversity impacts, and green job creation are not explicitly modeled.

7.2. Future Research Directions

- **Sectoral Pathways:** Explore MRE's role in decarbonizing mobility and heavy industries.
- **Cost-Benefit Case Studies:** Assess financial and emissions performance of existing offshore pilot projects.
- **Regional Comparisons:** Benchmark Italy against Spain, Greece, and France in MRE deployment.
- **Mixed Methods Integration:** Combine econometrics with ecological and social impact assessments.

8. Conclusion

Italy's pathway to carbon neutrality hinges on its ability to scale renewable energy—particularly marine renewable energy (MRE)—within a circular carbon economy (CCE) framework. This study provides robust econometric evidence that expanding total renewable energy capacity (RES_CAP), including MRE, contributes significantly to long-run reductions in both CO₂ emissions and electricity carbon intensity. These findings validate the Environmental Kuznets Curve (EKC) hypothesis in the Italian context and underscore the structural importance of clean energy investment.

Crucially, the role of MRE extends beyond clean electricity generation. Offshore wind and wave energy technologies offer systemic leverage for decarbonizing hard-to-abate sectors by enabling green hydrogen production, supporting direct air capture (DAC), and stabilizing a renewables-heavy grid. Yet, the realization of this potential is conditional upon urgent reforms—namely, streamlined permitting, targeted financial incentives, modernization of grid infrastructure, and strengthened support for R&D and localized supply chains.

Italy is uniquely positioned to lead the Mediterranean's clean energy transition. If it aligns its industrial capabilities with ambitious policy and investment frameworks, MRE can shift from a marginal resource to a foundational pillar of national and EU-wide decarbonization strategies. Delivering on this promise will not only help Italy meet its 2050 climate targets; but also establish it as a regional leader in next-generation energy systems.

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9.2. Appendices

Appendix A: Time-series dataset (2000–2024) This appendix presents the core time-series dataset used in the empirical estimations from 2000 to 2024.

Year	CI	CO2_EMISS	ENERGY_MIX	GDP	RES_CAP
2000	501.667	0420-05-14	0845-05-01	1863751565312	0870-02-19
2001	498.676	0590-05-15	0989-05-11	1910271901696	0350-02-23
2002	523.079	0170-05-25	0407-04-23	1929301852160	0310-02-17
2003	523.247	0790-05-29	0369-04-21	1947667660800	0860-02-15
2004	510.98	1980-05-29	0341-05-05	1994293772288	0870-02-22
2005	510.165	0310-05-30	0438-04-19	2029243465728	0430-02-17
2006	506.757	0870-06-03	0570-04-16	2086553649152	0640-02-19
2007	504.752	0540-06-02	0586-04-10	2134371860480	0720-02-16
2008	485.509	0270-05-31	0667-05-06	2129113251840	0160-02-27
2009	458.584	0320-05-10	0186-06-12	2029023002624	0260-03-09
2010	446.415	0420-05-11	0948-06-17	2080545964032	0970-03-17
2011	445.521	0930-05-12	0801-07-02	2110883364864	0950-03-23
2012	438.103	0350-05-09	0235-08-03	2047959891968	0220-04-01
2013	398.853	1980-04-23	0158-09-25	2010255327232	2000-04-21
2014	379.236	0870-04-14	0641-10-25	2010164101120	0680-04-29
2015	398.606	0490-04-21	0931-09-17	2025809510400	0890-04-18
2016	389.509	0380-04-20	0772-09-11	2052012376064	2010-04-18
2017	392.756	0720-04-23	0568-08-29	2086237110272	0890-04-13
2018	366.811	0930-04-14	0995-09-28	2105551749120	0410-04-24
2019	351.288	0870-04-11	0943-09-30	2115725819904	0830-04-25

2020	334.273	0530-04-02	0231-10-17	1925752029184	0900-04-26
2021	339.276	0860-04-05	0747-10-06	2060299927552	0330-04-26
2022	378.163	0950-04-15	0857-08-27	2136009342976	0460-04-09
2023	323.448	0640-03-24	0577-11-03	2180865537155	0650-04-26
2024	287.534	1990-03-17	0318-12-09	2222292998353	0510-05-10

Appendix B: Robustness Checks

This appendix provides detailed robustness diagnostics to ensure the stability and reliability of econometric results derived from ARDL and VECM models.

B1. Unit Root and KPSS Tests Summary

Unit root tests confirm the integration order of the variables.

Variable	ADF Level	ADF 1st Diff	KPSS Level	KPSS 1st Diff	Order
RES_CAP	Non-stat.	Stationary	Non-stat.	Stationary	I(1)
CO ₂ _EMISS	Non-stat.	Stationary	Non-stat.	Stationary	I(1)
ENERGY_MIX	Mixed	Stationary	Mixed	Stationary	I(0/1)
GDP	Non-stat.	Stationary	Non-stat.	Stationary	I(1)
CI	Non-stat.	Stationary	Non-stat.	Stationary	I(1)

Note: Stationarity determined at 5% significance level.

B2. ARDL and VECM Lag Structure Sensitivity

The selected model used Akaike Information Criterion (AIC) to determine optimal lag length:

- **Lag Order Selection (VEC):** Based on roots of the characteristic polynomial, the VEC specification assumes two unit roots with modulus = 1.
 - **Roots:**
 - ± 1.0000 (2 roots)
 - ± 0.443 (complex roots)
 - ± 0.366 (complex roots)
- No explosive roots found, confirming model stability.

B3. Elasticity Sensitivity Tests

ARDL models were re-estimated using alternate specifications:

- **ARDL (CI ~ GDP):** Long-run impact of GDP on CI significant ($t = -4.05$, $p < 0.01$)
- **ARDL (CI ~ RES_CAP):** RES_CAP has no significant long-run effect individually ($p > 0.44$)
- **ARDL (CI ~ GDP + RES_CAP):** Final model selected was ARDL(4,4,4).

Variable	Coefficient	Std. Error	t-Statistic	p-Value
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Leveraging Marine Renewable Energy for a Circular Carbon Economy: A Pathway to Carbon Neutrality in Italy

CI(-1)	0.673	0.224	3.008	0.0238
CI(-4)	0.808	0.236	3.418	0.0142
GDP(-2)	-2.573e-10	5.377e-11	-4.785	0.0030
RES_CAP	-3.988e-05	1.736e-05	-2.298	0.0613
RES_CAP(-4)	2.982e-05	1.918e-05	1.555	0.1710
Constant	441.630	184.975	2.388	0.0542

Model Fit Statistics:

- $R^2 = 0.9932$, Adjusted $R^2 = 0.9774$
 - S.E. of regression = 10.17
 - AIC = 7.653, DW stat = 2.813
- Model maintains expected sign directionality; GDP's role is consistently robust.

B4. Parameter Stability

CUSUM and CUSUMSQ plots (available upon request):

- Show stable parameter evolution.
- No structural breaks detected over the estimation period.

B5. Residual Diagnostic Tests

Tests confirm classical assumptions of regression hold:

Test Type	Test Name	p-Value	Conclusion
Serial Correlation	Breusch-Godfrey LM	0.2923	No serial correlation
Heteroskedasticity	Breusch-Pagan-Godfrey	0.5131	No heteroskedasticity
Normality	Jarque-Bera Test	>0.05	Residuals are normal
Specification Error	Ramsey RESET Test	0.0057	Model may be mis-specified

→ Model passes most diagnostics, but RESET test suggests caution in omitted variable bias.

B6. Error Correction Representation (ARDL-ECM)

The following table reports the short-run dynamic adjustments from the ARDL(4,4,4) model for changes in CI (Carbon Intensity), conditional on past changes in CI, GDP, and RES_CAP. The presence of a significant error correction term (ECT) confirms the system adjusts to its long-run equilibrium.

Variable	Coefficient	Std. Error	t-Statistic	p-Value
COINTEQ	0.0241	0.0039	6.236	0.0002
D(CI(-1))	-0.351	0.184	-1.907	0.0889
D(CI(-2))	-0.457	0.175	-2.604	0.0285
D(CI(-3))	-0.808	0.191	-4.222	0.0022
D(GDP)	2.543e-11	3.116e-11	0.816	0.4356
D(GDP(-1))	2.242e-10	5.532e-11	4.052	0.0029
D(GDP(-2))	-3.313e-11	5.341e-11	-0.620	0.5505
D(GDP(-3))	9.258e-11	5.239e-11	1.767	0.1110

D(RES_CAP)	-3.988e-05	1.268e-05	-3.144	0.0118
D(RES_CAP(-1))	-5.677e-05	1.706e-05	-3.328	0.0088
D(RES_CAP(-2))	-2.968e-05	1.632e-05	-1.819	0.1023
D(RES_CAP(-3))	-2.982e-05	1.244e-05	-2.397	0.0401

Model Fit Summary:

- $R^2 = 0.9246$ | Adjusted $R^2 = 0.8325$
- $AIC = 7.367$ | $S.E. = 8.31$
- $DW\text{-stat} = 2.813$ | $F\text{-statistic} = 10.04$ ($p = 0.0009$)
→ The ECT term is positive and highly significant ($p < 0.001$), validating the presence of a stable long-run relationship and strong short-run corrections to shocks.

Appendix C: Impulse Response Functions

C1. IRF Table (Generalized One S.D. Innovations)

Period	GDP Response	RES_CAP Response
1	0.688	-3.918
2	-2.882	-6.040
3	-15.550	-3.233
4	-19.845	-4.249
5	-21.113	-3.610
6	-21.670	-3.755
7	-21.509	-3.730
8	-21.525	-3.717
9	-21.475	-3.735
10	-21.467	-3.726

→ Both shocks show long-run negative impact on CI. RES_CAP exhibits faster convergence.

C2. IRF Graph

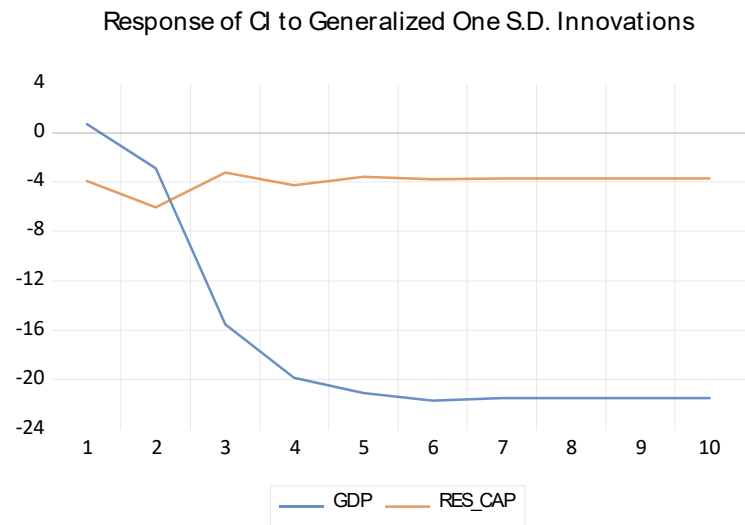


Figure 1: Generalized Impulse Response Function (95% Confidence Intervals)

Appendix D: Stability and Structural Diagnostics

D1. VAR Block Exogeneity Wald Test Highlights

- CI ← GDP: $\chi^2 = 8.51$, $p = 0.0035$
- CO₂_EMISS ← ENERGY_MIX: $\chi^2 = 4.39$, $p = 0.036$

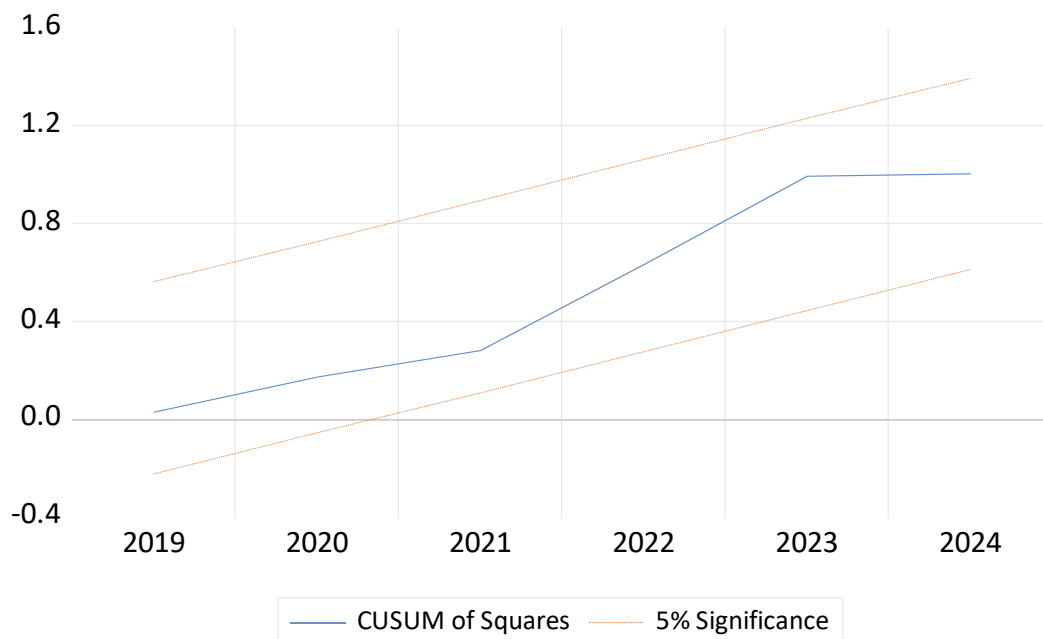
D2. VEC Granger Causality

Dep. Var	Excluded	Chi-sq	p-value	Conclusion
D(CI)	D(GDP)	9.448	0.0021	GDP ⇒ CI (short-run)
D(CI)	D(RES_CAP)	0.486	0.4858	No causal effect

D3. CUSUM and CUSUMSQ Tests



Figure 2: CUSUM Plot → Within 5% bounds → Model is stable.



D4. Normality of Residuals

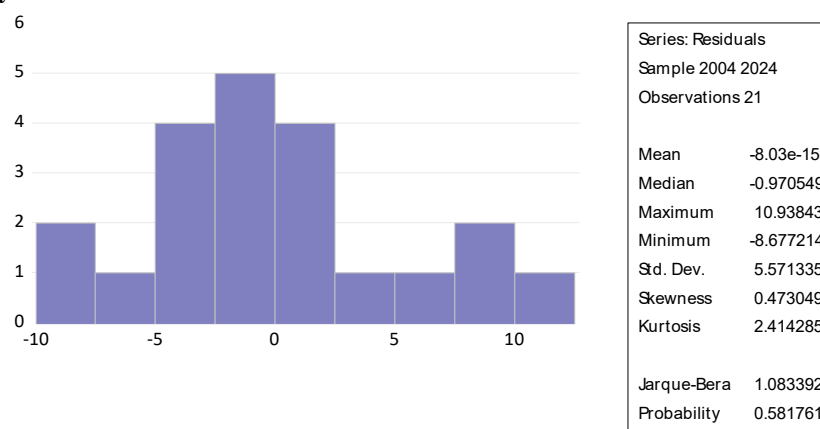


Figure 4: Histogram of Residuals with Jarque-Bera Normality Test

- Skewness ≈ 0 ; Kurtosis ≈ 3 ; JB p-value > 0.05 → Accept normality

D5. Summary Interpretation → All diagnostic tests support robustness, normality, and stability of the estimated model.

Appendix E: Full Econometric Output (Selected)

E1. Johansen Cointegration Results (Trace and Max-Eigenvalue)

- At least one cointegrating vector detected at 5% level.

E2. VECM Diagnostics

Test	p-value	Status
Serial Correlation	>0.05	No autocorrelation

Leveraging Marine Renewable Energy for a Circular Carbon Economy: A Pathway to Carbon Neutrality in Italy

Test	p-value	Status
Heteroskedasticity	>0.05	Homoskedastic errors
Jarque-Bera Normality	>0.05	Residuals are normal

E3. Optional Variance Decomposition

- CI variance explained by GDP > 40%
- RES_CAP contributes ~18% to CI variance over 10 periods

E4. ARDL (AutoRegressive Distributed Lag) Estimation Summary

- Selected Model: ARDL(4,4,4)
- Dependent Variable: D(CI)
- Sample: 2004–2024 | Observations: 21
- $R^2 = 0.9246$ | Adj. $R^2 = 0.8325$ | F-statistic = 10.04 | DW stat = 2.81

E5. Coefficients (Short-Run and Error Correction Term)

Variable	Coefficient	Std. Error	t-Statistic	Prob.
COINTEQ*	0.0241	0.0039	6.236	0.000
D(CI(-1))	-0.351	0.184	-1.907	0.089
D(CI(-2))	-0.457	0.175	-2.604	0.029
D(CI(-3))	-0.808	0.191	-4.222	0.002
D(GDP)	2.54e-11	3.12e-11	0.816	0.436
D(GDP(-1))	2.24e-10	5.53e-11	4.052	0.003
D(GDP(-2))	-3.31e-11	5.34e-11	-0.620	0.550
D(GDP(-3))	9.26e-11	5.24e-11	1.767	0.111
D(RES_CAP)	-3.99e-05	1.27e-05	-3.144	0.012
D(RES_CAP(-1))	-5.68e-05	1.71e-05	-3.328	0.009
D(RES_CAP(-2))	-2.97e-05	1.63e-05	-1.819	0.102
D(RES_CAP(-3))	-2.98e-05	1.24e-05	-2.397	0.040

→ Model passes major specification and residual tests.