22nd International Conference on Renewable Energies and Power Quality
(ICREPQ'24) Bilbao (Spain), 26th to 28th June 2024
Renewable Energy and Power Quality Journal (RE&PQJ)
ISSN 2172-038 X, Volume No.22, September 2024

Efficiency of R&D&I Investment in Energy Technology in Spain

Daiane Rodrigues dos Santos[1], Tuany Esthefany Barcellos de Carvalho Silva[2] and Reinaldo Castro Souza[2]

[1] State University of Rio de Janeiro, Department of Economics
São Francisco Xavier, Rio de Janeiro (Brazil)
Phone: +055 (21) 2334-2334

[2] Pontifical Catholic University of Rio de Janeiro, Department of Industrial Engineering
R. Marquês de São Vicente, Rio de Janeiro (Brazil)
Phone: +055 (21) 3527-1092

Abstract.

The growing concern over climate change has propelled the urgent need for technological innovation in clean energies, investing in Research and Development (R&D&I), a fundamental pillar for the global energy transition. This study focused on Spain, an active Organization for Economic Cooperation and Development (OECD) member, to examine and discuss the relationships between carbon dioxide () emissions, renewable energy generation, R&D&I investment, and GDP. Through data analysis, economic and environmental trends were highlighted, and the interaction between variables in the context of sustainability policies was explored. The results indicated a negative relationship between the increase in renewable energy generation and emissions, in line with international efforts to mitigate climate change. The robust statistical analysis provides insights into the effectiveness of Spain's energy and environmental policies and suggests a continuous trajectory of emissions reduction. This study modeled and discussed the importance of ongoing investment in R&D&I and implementing policies that reinforce the transition to a cleaner and more sustainable Spanish energy system.

Key words. Renewable Energy, CO2 Emissions, R&D&I Investment, Econometric Modeling, Energy Policy.

1. Introduction

The global concern surrounding climate change has underscored the critical need for Research and Development (R&D&I) investment to advance cleaner and more sustainable energy technologies. As [1] highlighted, accelerating technological innovation in energy is essential to counter global climate change and build a clean energy system. At the forefront of this transformative drive are the Organization for Economic Co-operation and Development (OECD) member countries, which acknowledge R&D&I as a pivotal lever to hasten the energy transition and meet international environmental commitments. As part of this collective, Spain significantly shapes guidelines and policies that encourage technological innovation. Investing in R&D&I is a matter of environmental responsibility and a strategic move to boost the economy and ensure energy security by reducing reliance on fossil fuels and mitigating risks associated with the volatility of global energy prices. At a recent OECD meeting, Spain's role in the negotiations highlighted the importance of a collaborative and integrated approach to tackling climate challenges. Spain has demonstrated its commitment to the sustainability agenda by advocating for increased investment in R&D&I, not just in absolute terms but also as a percentage of its GDP. Spain's strategy for technological advancement in renewable energies and reducing carbon dioxide emissions aligns with the objectives outlined in the Paris Agreement and the United Nations Sustainable Development Goals. This proactive stance strengthens Spain's position as a leader in clean energy technologies and sets a precedent for other nations to follow, promoting collective action toward a sustainable future.

Carbon dioxide (CO2) emissions significantly contribute to climate change by playing a central role in the greenhouse effect. Combustion of fossil fuels and land use changes drive atmospheric CO2 concentrations, which in turn trap solar heat, leading to global warming and changes in the Earth's climate system [2]. These changes lead to higher average global temperatures, sea-level rise, and an increase in extreme weather events like heatwaves, droughts, and severe flooding [2]. Studies highlight a direct link between the amount of $CO2$ emissions, and the severity of observed and predicted climate changes [3].

Experts are implementing and researching various strategies globally in response to the urgent need to cut CO2 emissions. The Paris Agreement has created an international framework for decarbonization, with goals to keep the global temperature rise well below 2°C above pre-industrial levels, aiming for 1.5°C, which will require substantial and rapid reductions in greenhouse gas (GHG) emissions [4]. Renewable energy is a key solution by providing a low-carbon alternative to fossil fuels and gaining economic competitiveness through technological progress and political support [5]. Moreover, pursuing energy efficiency and technological innovations in transportation, industry, and construction is crucial for meeting climate targets [5].

The scope of this study will concentrate on analyzing available data about Spain's renewable energy sector, and emission reduction efforts, and aligning these with international climate objectives. We will examine Spain's progress in integrating renewable energy sources into the national grid, the effectiveness of policy measures in promoting sustainable energy, and the impact of these measures on $CO2$ emissions.

This study constitutes a substantial contribution to the scientific landscape that explores the relationship between CO2 emissions, renewable energy generation, research, development, and innovation (R&D&I) investment, and economic growth, with a specific focus on the Spanish context. The work presents three main innovations:

(i) Advanced Econometric Model: An innovative econometric model is proposed that incorporates the complex dynamics of the variables under analysis, including linear trends, non-periodic components, first-order autoregression (AR(1)), and carefully selected explanatory variables. The robustness of this model is demonstrated by its ability to accurately explain the variability of CO2 emissions, without the need for normality assumptions in the data. This robustness enhances the model's applicability to different datasets, providing a valuable tool for future analyses.

(ii) R&D&I Analysis: In addition to simplistic approaches, this study conducts a detailed analysis of the impact of R&D&I investment in the renewable energy sector. The results indicate that increased investment in R&D&I contributes to the development of new energy technologies and reduces the production costs of renewable energy, thereby driving clean energy generation and mitigating CO2 emissions.

(iii) Policy Directives: The findings of this study offer important information for those interested in promoting environmental sustainability in line with economic growth. The combination of these innovations makes this study a significant contribution to the literature on energy and the environment, providing new perspectives on the interactions between the variables under analysis and guiding decision-makers in the search for a more sustainable future.

2. Theoretical framework

Previous studies show that Research and Development (R&D&I) investments significantly and positively impact the energy market, proving these investments are essential for innovation and energy efficiency. The research by Johnstone and others [7] in 2010 highlighted that increasing R&D&I spending could speed up the development and deployment of renewable energy technologies, cutting production costs and boosting market competitiveness. Moreover, [8] work from 2012 suggests that R&D&I funding in the energy sector sparks the rise of low-carbon technologies, fostering an energy transition to cleaner and more sustainable sources.

According to [1], government expenditures directed towards green technologies are at the heart of these policies, driven not only by energy supply security but also by low-carbon energy systems and environmental protection. Thus, promoting innovative/clean energies was already part of the European Commission's energy agenda as one of the critical items to fulfill the ambitious goals of the Paris Agreement.

The connection between CO2 emissions and their environmental impact is direct and concerning. The IPCC's [2] Fourth Assessment Report from 2007 states that rising atmospheric CO2 levels are the primary driver of climate change, leading to significant shifts in global climate patterns. Smith et al. [9] in 2014 reinforced this scientific consensus, finding that carbon dioxide emissions heighten the greenhouse effect, resulting in global warming and increasingly frequent and severe extreme weather events. These studies collectively emphasize the critical need to cut CO2 emissions through strategic R&D&Iinvestments capable of mitigating long-term adverse environmental impacts.
Recent research underscores the critical role of public investment in R&D&I in advancing renewable energy technologies. That strategic government funding in solar energy R&D&I has a multiplier effect, substantially increasing private sector investment and patent generation. Their findings suggest a strong positive correlation between public R&D&I expenditure and the rate of innovation in solar technologies [10]. A comprehensive analysis of wind energy projects demonstrates that public investments not only enhance technological capabilities but also attract international partnerships, leading to more rapid adoption of wind energy on a global scale.
The trajectory of public investment in Research, Development, and Innovation (R&D&I) in energy technology over recent decades in Spain not only illustrates the growing appreciation of science and technology as pillars of development but also the response to economic and political fluctuations. Starting with a modest investment of 1.34 million euros in 1974, there was an exponential growth through to 2021. The figures registered a significant leap during the 1980s, reaching 9.8 million, and again at the turn of the millennium, where spending peaked at 63.3 million. Following a drop to 10.84 million, likely reflecting periods of fiscal adjustment or economic crises, investments resumed an upward trajectory, culminating in a substantial 162.4 million in 2011.

Retraction periods are also apparent, such as the decrease to 47.7 million in 2013 and a more pronounced dip to 29.25 million in 2016, reflecting the volatility of government commitments to the R&D&I sector in the Spanish energy market. However, public investment demonstrated resilience and a capacity to recover, rising to 70.2 million in 2018. Despite a further reduction in subsequent years, the commitment to R&D&I maintained an overall growth trend, with investment reaching 90.8 million in 2021. This evolution reflects the strategic recognition of R&D&I as a driver of sustainable progress and international competitiveness [6].

Over the past few years, the European Union has established an ambitious energy agenda in line with the objectives of the Paris Agreement, aiming at a transition to cleaner and more sustainable energy systems. One of the pillars of this transformation is the investment in research, development, and demonstration (R&D&I) of energy technologies, recognizing the vital role that technological innovation plays in reducing carbon footprints and promoting the supply of clean energy. In this context, the government budget allocated to R&D&I in energy technology emerges as the primary input to encourage innovations that contribute to the supply of clean energy and reduce carbon emissions. [1] investigated the impact of this budget on two critical aspects: the supply of cleaner energy, measured by the contribution of renewable energies to the total primary energy supply, and the carbon footprint (CFP) of European countries from 1985 to 2016.

According to [1], energy technological innovation policies in Europe are essential to reduce the dependence on fossil fuels and to mitigate environmental issues arising from this dependence. This synergy can create opportunities for innovative energy policies to successfully realize Europe's sustainable energy transition, which is crucial to achieving multiple climate objectives. However, despite the immense potential of energy technology innovations, the development of green technological innovations faces enormous challenges primarily due to market failures and structural differences and research capabilities among European countries.

The relationship between CO2 emissions and their environmental impact is clear and concerning. The Fourth Assessment Report of the IPCC (2007) states that CO2 concentrations in the atmosphere are the primary driver of climate change, leading to significant shifts in global climate patterns. Notably, carbon dioxide emissions intensify the greenhouse effect, resulting in global warming and increasingly frequent and severe extreme weather events. Furthermore, adopting renewable energies and sustainability practices are fundamental steps in this direction. The International Energy Agency (IEA) reports that transitioning to clean energy sources helps reduce carbon dioxide emissions and supports energy security and sustainable economic development [6]. To achieve the goals of the Paris Agreement and limit the global temperature rise to 1.5°C above pre-industrial levels, it is essential to implement effective policies, fiscal incentives, and regulations that promote the economy's decarbonization. Collaboration among countries, the private sector, and civil society is essential to foster innovation and adopt clean technologies, aiming for a future with low carbon emissions and resilience to climate change.
Global carbon dioxide emissions have followed a concerning upward trajectory over the past decades. According to the BP Statistical Review of World Energy, from June 2022, the world's total CO2 emissions from energy stood at 11,192.8 million tonnes in 1965. This number consistently increased, reaching 11,696.6 million tonnes the following year. The progression continued with emissions rising to 12,059.0 million tonnes, and the growth trend persisted, with emissions hitting 12,704.8 million tonnes. As we entered the new millennium, emissions surged significantly to 13,489.2 million tonnes, and this rise continued steadily to 14,297.0 million tonnes. After some fluctuations, 2020 marked a decline to 32,078.5 million tonnes, possibly influenced by global factors such as the COVID-19 pandemic. However, there was a rebound in 2021, with emissions climbing to 33,884.1 million tonnes, highlighting the ongoing and challenging task of reducing carbon emissions and combating climate change globally.
CO2 emissions in Spain, as reported in the BP Statistical Review of World Energy from June 2022, climbed from 80.4 million tonnes in 1965 to a peak of 340.1 million tonnes in 2005, reflecting the country's industrial and energy growth. After reaching this peak, emissions demonstrated a declining trend, with some fluctuations, dropping to 245.7 million tonnes in recent years, indicating significant progress towards carbon emission mitigation and a shift towards cleaner energy sources, in line with global efforts to combat climate change.

This study on the efficiency of R&D&I investments in energy technology in Spain underscores the strategic importance of an innovative and sustainable approach in the energy sector. As Spain progresses towards fulfilling its environmental commitments and aligning with global guidelines for carbon emission reduction, it is clear that R&D&I efforts have played a pivotal role. Continued and strategic investment in R&D&I is essential not just for developing cleaner and more efficient energy technologies, but also for strengthening the economy, enhancing energy security, and positioning Spain as a leader in the transition to a sustainable energy future. This study reinforces the necessity for focused public policies and effective collaboration among academic institutions, industry, and the government to sustain Spain's positive and innovative trajectory in the global energy landscape.

For the modelling of multivariate series, the State Space Model was used. The models in question represent a flexible and powerful approach in the field of time series analysis, allowing for the modelling of a wide variety of dynamic processes. The ability of these models to incorporate unobservable components, such as trends and cycles, as well as the ability to handle irregular or missing observations, makes them particularly useful in economic and financial applications (Durbin & Koopman, 2012). The state space structure is composed of two main equations: the observation equation, which relates the observed variables to latent states, and the transition equation, which describes the evolution of these states over time. This framework is so general that many classical time series models, such as ARIMA and seasonal models, can be formulated as special cases of state space models (Harvey, 1989).

3. Model

State Space Models, as proposed by Harvey and Koopman, offer a way to model time series. They comprise two main equations: the observation (or measurement) equation and the transition (or state) equation. The matrix form of these equations simplifies computation, especially when employing the Expectation-Maximization (EM) algorithm for parameter estimation. The equations are described as follows.

Observation Equation:

$$y_t = Z_t \alpha_t + \varepsilon_t, \quad \varepsilon_t \sim N(0, H_t) \quad (1)$$

State Equation:

$$\alpha_{t+1} = T_t \alpha_t + R_t \eta_t, \quad \eta_t \sim N(0, Q_t) \ (2)$$

In which y_t is the observation vector at time (t). Z_t is the matrix that relates the state vector α_t with the observation vector y_t.

$$Z_t = [1, 0, 0, \beta_1, \beta_2, \beta_3] \ (3)$$

where β's are the coefficients for explanatory variable.

$$\alpha\_t = [Level\_t, \quad Slope\_t, \quad AR(1)\_t, \quad LP\&D/GDP\_t, \quad LPIB\_t, \quad LRenewables\_t] \ (4)$$

ε_t is the observation error vector (or innovations) at time (t), which is assumed to be normally distributed with zero mean and covariance matrix H_t.

$$\mathrm{H_t} = [\sigma_\varepsilon^2] \ (5)$$

It represents the uncertainty or noise associated with the observations. α_{t+1} is the state vector at the next time period, $t + 1$. This part of the equation defines how the state vector evolves over time. α_{t+1} is the transition matrix that describes the dynamics of the state vector. It defines how the current state affects the future state.

$$T_t = \begin{bmatrix} 1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & \rho & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} (6)$$

R_t is the control matrix that influences how the state innovation vector η_t affects the state transition.

$$R_t = [1;\ 0] \ (7)$$

The state innovation vector η_t) at time (t) is also assumed to be normally distributed with zero mean and covariance matrix Q_t which represents the uncertainty or random shocks that affect the evolution of the state vector.

$$Q_t = \ diag\left(\sigma_{level}^2, \sigma_{slope}^2, \sigma_{AR(1)}^2, \sigma_{irreg}^2\right) \ (9)$$

One of the main benefits of state space models is their ability to integrate the Kalman Filter, a recursive algorithm that delivers optimal estimates of latent states based on the available information up to the current point in time. The Kalman Filter excels because it updates state estimates in real time as new observations become available (Kalman, 1960). Furthermore, state space models eliminate the need for time series to be stationary, which stands as a significant advantage over many traditional methods. They directly handle trends, seasonality, and other forms of non-stationarity in their state components, removing the need for prior data transformations such as differencing, which are often used to induce stationarity (Hamilton, 1994). This feature makes state space models invaluable tools for analysts and researchers dealing with complex and non-stationary economic and financial data.

State space models, as utilized within the context of our study, play a pivotal role in thoroughly examining and elucidating complex relationships inherent in time series data pertaining to carbon dioxide (CO2) emissions, renewable energy generation, Research and Development (R&D&I), and Gross Domestic Product (GDP) within the Spanish context. The utility of state space models extends across various dimensions critical for rigorous academic analysis and policy formulation.

Firstly, these models demonstrate proficiency in time series analysis and forecasting, facilitating the discernment of temporal trends and patterns pertinent to CO2 emissions, renewable energy utilization, and their interplay. Such predictive capabilities are foundational for evidence-based decision-making processes concerning sustainable energy policies and environmental stewardship initiatives.

Secondly, the capability of state space models to estimate latent states, encompassing underlying trends, seasonal variations, and irregular fluctuations within the dataset, contributes significantly to unraveling the nuanced dynamics steering CO2 emissions and renewable energy trends. This latent state estimation constitutes a fundamental aspect for identifying and understanding the key drivers influencing emissions trajectories and designing targeted interventions accordingly.

Moreover, state space models excel in anomaly detection and monitoring, adeptly identifying atypical patterns within the data, such as abrupt spikes or declines in emissions de CO2 or renewable energy output. This capability is instrumental in continuously evaluating the efficacy of environmental interventions, facilitating prompt corrective actions and adjustments as necessitated by evolving circumstances.

The integration of exogenous variables, such as R&D&I investment in renewable energies and economic indicators like GDP, further enhances the analytical robustness of state space models. By incorporating these external factors, the models achieve a more holistic and nuanced analysis, elucidating the multifaceted influences shaping CO2 emissions trajectories and renewable energy dynamics.

Lastly, the adaptability and resilience of state space models in accommodating dynamic environments and non-linear relationships inherent in environmental and economic datasets render them indispensable tools for long-term planning and decision-making. Their ability to capture and model complex interactions and non-stationarities underscores their value in academic research, contributing substantively to the discourse on sustainable energy transitions and climate change mitigation strategies.

In summary, the formal and academic application of state space models within our study framework serves as a robust analytical framework, enabling a nuanced understanding of the intricate interdependencies among CO2 emissions, renewable energy utilization, R&D investments, and economic indicators within Spain.

4. Results

Fig. 1 presents the four series used in the current article. The dependent variable in this study is Carbon Dioxide Emissions from Energy (Million tonnes of carbon dioxide), and the independent variables are: (i) Electricity generation from renewable sources (GWh), (ii) investment in R&D&I in renewable energies per thousand units of GDP, and (iii) Nominal Gross Domestic Product - Nominal GDP (in millions). The data are in logarithmic form and offer a valuable insight into Spain's economic and environmental trends over nearly half a century.

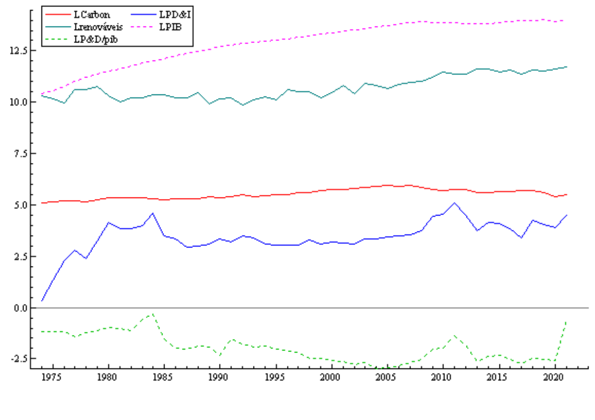

Fig. 1. Selected series in logarithmic scale from 1974 to 2021.
Source: IEA and Energy Institute (EI)

Fig. 1 clearly illustrates Spain's carbon dioxide (CO2) emissions trend from energy consumption, which climbed steadily until the early 2000s, mirroring the country's industrial expansion and heightened reliance on fossil fuels. After peaking in the early 2000s, emissions began a notable decline post-2008, signaling a shift towards energy sources that emit less CO2. Concurrently, electricity generation from renewable sources has been on the rise, with a marked surge apparent after the year 2000. This significant increase likely stems from concerted global efforts to tackle climate change through the promotion of renewable energy.

This upward trend in renewable energy generation is in harmony with pivotal global environmental governance milestones. The Kyoto Protocol's entry into force in 2005, as one of the earliest international treaties imposing binding emission reduction targets on developed nations, has undoubtedly spurred investments in green energy. Additionally, the OECD's pivotal role in steering its member countries towards sustainable development has been influential. The Paris Agreement, ratified in 2015, stands out as a landmark accord, galvanizing global action by setting a framework for countries worldwide to curb greenhouse gas emissions and cap global temperature rise. Investments in clean energy research and development (R&D&I) per thousand units of GDP, as depicted in Fig. 1, have shown significant fluctuations. This volatility indicates that R&D&I investment decisions are subject to a myriad of influences, from shifting economic landscapes and policy directions to technological breakthroughs.

The steep downturn observed in 2020 coincides with the global onslaught of the COVID-19 pandemic, which understandably redirected focus and funding toward pressing public health challenges and economic stabilization measures. The subsequent rebound in 2021 signals a swift bounce-back in R&D&I investment, pointing to a resilient commitment to advancing clean energy technologies.

The model adopted for the analysis of carbon emissions in Spain showed good adherence to the data, as evidenced by a Log-Likelihood value of 136.719. This robust indicator underscores the model's effectiveness in capturing the complexity of the data, offering a high degree of likelihood in the description of the time series. The combination of a low forecast error with a detailed analysis of the structural nuances of the data reinforces confidence in the future projections provided by the model, a fundamental aspect for the formulation of efficient energy and environmental policies.

Table 1 presents the parameter estimates. As can be seen the level variance, estimated at 0.000964940, indicates the inherent variability in the underlying state of the process, and with a Q-Ratio of 1.000, it suggests that this component is fully accounted for in the model. The slope variance, significantly smaller at 0.000208731, reflects the variability in the trend's slope with a Q-Ratio of 0.2163, indicating a lesser but non-negligible contribution to the overall model variance. The autoregressive component of order 1 (AR(1)) variance is 0.000362469, which is indicative of the extent to which consecutive errors are correlated, while the irregular variance, the smallest at 0.0000172586, captures the random, unsystematic fluctuations in the model.

Further scrutiny of the autoregressive parameter reveals an AR coefficient of 0.90000, pointing to a strong persistence in the time series data. The state vector analysis, which evaluates the final state regression effects, illustrates a negative level parameter (-5.028) with a probability of 0.03756, signifying a statistically significant effect at conventional levels. The slope parameter (-0.05326) also shows significance with a probability of 0.04346, denoting a slight but meaningful downward trend.

The regression effects on the final state are observed in the positive coefficient for LP&D/GDP (0.03205), which is statistically significant at the 0.01632 probability level, indicating a positive effect. LGDP's coefficient (0.86624) is highly significant with a probability of 0.00001, underscoring a positive relationship, the Lrenewables coefficient (-0.13543) is significant at the 0.00000 probability level, reflecting a substantial negative impact on the dependent variable.

Table 1 – Estimations using Expectation-Maximization (EM) algorithm

Parameter	Estimate	Standard Error	t-Value	Prob	Q-Ratio
Variances of disturbances					
Level Variance	0.000964940				1.000
Slope Variance	0.000208731				0.2163
AR(1) Variance	0.000362469				0.3756
Irregular Variance	0.0000172586				0.01789
AR(1) other parameters					
AR Coefficient	0.90000				
State vector analysis and Regression effects in final state					
Level	-5.028			0.03756	
Slope	-0.05326			0.04346	
LP&D/GDP	0.03205	0.01282	2.499	0.01632	
LGDP	0.86624	0.16653	5.201	0.00001	
Lrenewables	-0.13543	0.02040	-6.639	0.00000	

Source: Developed by the authors.

As can be seen in Table 2 and Fig. 3, the distribution of residuals approaches normality, with a value of 0.13040 in the normality test, suggesting that the underlying statistical hypotheses are respected. The Durbin-Watson statistic, close to 1.6006, indicates a modest residual autocorrelation but is still within acceptable limits, highlighting the adequacy of the model in capturing temporal correlations. Furthermore, the adjusted coefficient of determination (Rd^2), at 0.65225, confirms that the model is effective in explaining a significant portion of the variability observed in carbon emissions.

Table 2 - Summary statistics

Metrics	statistic
T	48.000
p	40.000
std.error	0.03869
Normality	0.13040
H(14)	12.411
DW	16.006
r(1)	0.096479
q	90.000
r(q)	-0.02369
Q(q,q-p)	17.062
Rd^2	0.65225

Source: Developed by the authors.

The perturbation variations reveal stability in the model's components, with the level and slope displaying low variability, implying an efficient capture of long-term trends and temporal dynamics without overreacting to random fluctuations. The AR(1) term, with a coefficient of 0.90000, introduces an explicit consideration of the process's memory, allowing the model to accommodate the persistence of carbon emissions in a theoretically coherent and empirically justified manner.

Regarding the analysis of the regression effects in the final configuration of the model in 2021, it provides invaluable economic and environmental insights. The coefficient for LP&D/GDP (log of the Research and Development to GDP ratio) is significant and slightly positive, suggesting that investment in R&D&Idoes not yet have a direct impact on carbon emissions. In turn, the log of renewable energy generation maintains a negative relationship, indicating that an increase in renewable energy generation is associated with a reduction in CO2 emissions, a result that supports the energy transition to cleaner sources. It should be noted that investment in Research and Development in renewable energies enables the increase of clean energy generation and facilitates their expansion (with a correlation of 0.57%). It is worth mentioning that the model with only one of these variables did not achieve a better statistical fit. Regarding Spain's GDP, it presents a positive coefficient, aligning with the hypothesis that economic growth, in the absence of effective mitigating measures, can lead to an increase in carbon emissions. These results are crucial for a deep understanding of the interactions between economic development, investment in technology, renewable energy generation, and environmental sustainability.

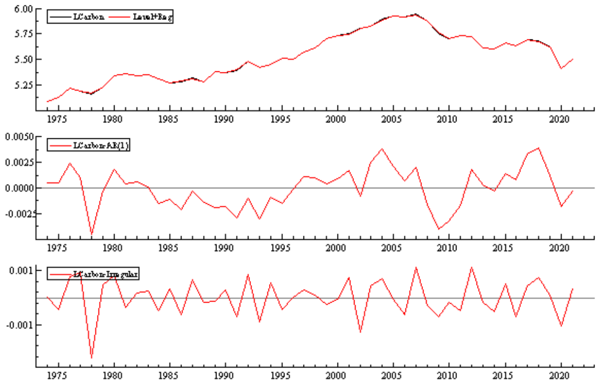

Fig.2. Model fitting
Source: Elaborated by the authors based on the collected data.

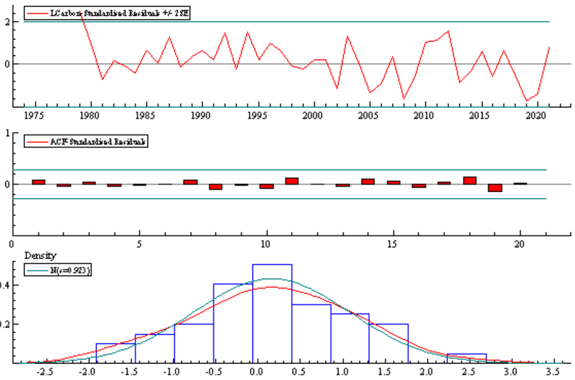

Fig. 3. Model residuals
Source: Elaborated by the authors based on the collected data.

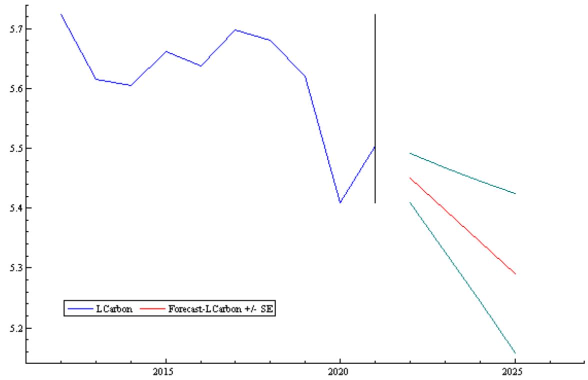

Fig. 4. Annual forecast of the dependent variable
Source: Elaborated by the authors based on the collected data.

Fig. 4 displays the annual logarithmic forecast for the 'Carbon Dioxide Emissions from Energy' series (measured in million tonnes of carbon dioxide). The model in use is comprehensive and multi-dimensional, incorporating a linear trend, irregular components, first-order autoregression (AR(1)), and a set of carefully selected explanatory variables: (i) electricity generation from renewable sources, measured in gigawatt-hours (GWh); (ii) research and development (R&D) investment in renewable energies, adjusted per thousand units of Gross Domestic Product (GDP) - LP&D/GDP; and (iii) Nominal GDP, expressed in millions.

Model projections indicate a progressive decrease in CO2 emissions for the post-2021 timeframe, as evidenced by point estimates and their corresponding 68% confidence intervals. Specifically, the initial estimate of 5.45063, with a standard error of 0.04172, sets confidence limits between 5.40891 and 5.49236. This declining trend in emissions consistently appears in subsequent periods, reaching a forecast of 5.29092 in the fourth analyzed time interval, despite an acknowledged increase in estimate variability, as reflected by the growing standard error and the widening of confidence intervals. Such an increase in projection uncertainty underscores the importance of continuous monitoring and strategic policy interventions to ensure the maintenance or amplification of this downward trend, aligning with environmental sustainability goals and climate change mitigation efforts.
This robust analysis highlights the relevance of the selected variables in the model and the imperative need to continuously monitor carbon dioxide emissions trends, as well as to implement policies that reinforce the observed outcomes, promoting sustainable and responsible development in the management of greenhouse gas emissions.

4. Conclusion

This study contributes significantly to understanding Spain's energy landscape through a comprehensive analysis that intertwines CO2 emissions, renewable energy generation, R&D&I investment, and economic growth. The econometric model developed in this research reveals a substantial negative correlation between the advancement of renewable energy technologies and CO2 emission levels, emphasizing the pivotal role of renewable energy investment in Spain's pursuit of environmental sustainability goals. Notably, the statistical robustness of the model, particularly evident in the elasticity coefficients of renewable energy production and R&D&I investment, underscores the efficacy of Spain's policy initiatives in steering the country towards a sustainable energy future.

The adherence of the model to statistical assumptions, demonstrated without requiring data normality, enhances its generalizability across diverse datasets, making it a valuable tool for future analyses. The methodological approach, integrating the EM (Expectation-Maximization) algorithm and the Kalman filter within a matrix framework, facilitates efficient parameter estimation and dynamic interpretation of time series data, offering nuanced insights into underlying trends.

Discussions within this study illuminate the complexities of the energy transition, especially regarding the synergistic impacts of R&D&I investment on both energy innovation and broader economic indicators. The model's forecasts project a promising reduction in CO2 emissions with increased renewable energy generation, contingent upon sustained or accelerated R&D&I investment rates.

This research's significance lies in its empirical contributions to environmental economics and policy formulation, providing evidence-based guidance on successful strategies employed by Spain and offering transferable insights for other nations. The econometric results underscore the effectiveness of coordinated policy efforts in addressing climate change challenges and progressing towards sustainable energy paradigms.

Furthermore, this study transcends Spain's borders, serving as a model for international policymakers striving to align economic development with environmental stewardship. By highlighting the interplay between renewable energy investment, technological advancement, economic growth, and environmental outcomes, this research aids in shaping informed policy decisions for a greener and more sustainable future globally.

References

[1] Kassouri, Y., Bilgili, F., & Peter Majok Garang, A. (2022). Are government energy technology research, development, and demonstration budgets converging or diverging? Insights from OECD countries. Technology Analysis & Strategic Management, 34(5), 563-577.

[2] IPCC. (2021). Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., et al. (eds.)]. Cambridge University Press. https://www.ipcc.ch/report/ar6/wg1/

[3] Le Quéré, C., et al. (2018). Global Carbon Budget 2018. Earth System Science Data, 10, 2141-2194. https://doi.org/10.5194/essd-10-2141-2018

[4] Rogelj, J., et al. (2016). Paris Agreement climate proposals need a boost to keep warming well below 2 °C. Nature, 534(7609), 631-639. https://doi.org/10.1038/nature18307

[5] IRENA. (2020). Renewable Power Generation Costs in 2019. International Renewable Energy Agency. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Jun/IRENA_Power_Generation_Costs_2019.pdf

[6] IEA. (2020). Energy Technology Perspectives 2020. International Energy Agency.

[7] Johnstone, N., Hascic, I., & Popp, D. (2010). Renewable Energy Policies and Technological Innovation: Evidence Based on Patent Counts. Environmental and Resource Economics, 45(1), 133–155. https://doi.org/10.1007/s10640-009-9309-1

[8] Aghion, P., Dechezleprêtre, A., Hemous, D., Martin, R., & Van Reenen, J. (2012). Carbon Taxes, Path Dependency, and Directed Technical Change: Evidence from the Auto Industry. Journal of Political Economy, 124(1), 1–51. https://doi.org/10.1086/669034

[9] Smith, S. J., Edmonds, J., Hartin, C. A., Mundra, A., & Calvin, K. (2014). Near-term acceleration in the rate of temperature change. Nature Climate Change, 4(4), 333–336. https://doi.org/10.1038/nclimate2209

[10] Siddik, A. B., Khan, S., Khan, U., Yong, L., & Murshed, M. (2023). The role of renewable energy finance in achieving low-carbon growth: contextual evidence from leading renewable energy-investing countries. Energy, 270, 126864.

[11] Kabir, M., Habiba, U. E., Khan, W., Shah, A., Rahim, S., Farooqi, Z. U. R., ... & Shafiq, M. (2023). Climate change due to increasing concentration of carbon dioxide and its impacts on the environment in 21st century; A mini-review. Journal of King Saud University-Science, 102693.