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BEYOND SUNLIGHT: HOW CO_2 EMISSIONS, COAL LOCK-IN, AND GLOBAL FINANCE SHAPE AUSTRALIA'S SOLAR ENERGY CONSUMPTION - AN ARDL ANALYSIS WITH ROBUSTNESS CHECKS

Soumaya Hechmi[1]

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[1] Imam Mohammad Ibn Saud Islamic University (IMSIU), Riyadh, Saudi Arabia

*Corresponding Author:
Soumaya Hechmi

Email:
sbhechmi@imamu.edu.sa

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ABSTRACT

This study examines the determinants of solar energy adoption in Australia between 1991 and 2023 using an Autoregressive Distributed Lag (ARDL) model. The results reveal long-run equilibrium relationships and short-run adjustment mechanisms between solar deployment and the most pertinent economic, environmental, and financial factors. The results reveal some significant findings. First, financial globalization shows a strong negative long-run effect on Solar Energy Consumption. (SEC), suggesting that international capital flows have previously endorsed fossil fuel systems rather than renewable transitions. Second, coal consumption illustrates a strong negative effect, confirming path dependency challenges. Thirdly, while CO_2 emissions and GDP per capita have a positive effect on SEC, population growth has a negative relationship, suggesting that urbanization may precede the establishment of renewable infrastructure. The study's policy implications underscore three strategic priorities: accelerating the transition away from coal and toward clean energy systems, transforming financial markets to encourage green investment, and channeling economic growth to build sustainable energy infrastructure. These are the proposals that have been advocated to address structural challenges for Australia's energy transition while taking advantage of the strengths that have been built. The research presents empirical evidence for integrated policy strategies in orchestrating economic development and decarbonization goals within resource endowments.

Keywords: *Solar energy consumption, coal consumption, financial globalization, CO2 emissions, population growth, economic growth, climate policy, Australia*

1. INTRODUCTION

The global drive towards low-carbon energy systems has become increasingly unprecedented than ever before as a result of the escalating climate crisis and shifting global climate obligations (Shukla et al., 2022). Solar energy, in particular, has emerged as a pillar for global decarbonization plans with adoption rates being shaped by complex interaction patterns among technological innovation, economic conditions, policy regimes, and institutional contexts (IRENA, 2024). This study considers these critical dynamics through the lens of Australia's distinctive energy environment - a high-income economy that is blessed with world-class solar resources but still grappling with entrenched fossil fuel dependence (AEMO, 2024). Australia has a compelling case study with its unique position as both a renewable energy leader and major exporter of fossil fuels, provoking the tensions that mirror broader challenges of resource-rich nations making energy transitions (Clean Energy Council, 2023). The country's experience is particularly informative given its rampant solar energy expansion over the past decade, which has come on top of unrelenting coal-fired electricity production and rising liquefied natural gas imports, offering a real-world laboratory to study energy transition paradoxes.

Australia's path to a lower-carbon energy future assumes specific significance when considering its decentralized policymaking regime, within which state and territory governments have each adopted strongly differentiated approaches to the use of renewable energy while participating in a national electricity market (AEMO, 2024). Australia's rich endowment of fossil fuels and sunny climate add to this multilevel governance system and contribute to a policy challenge in which economic, environmental, and energy security interests tend to jostle for prominence (Clean Energy Council, 2023). The nation's experience with solar adoption is also reflective of these tensions, both leading the world in per capita rooftop solar installation rates and grappling with scaling up renewable energy integration (Garnaut, 2021). These aspects create a good setting to examine the intersection of economic structure, energy systems, and policy choices to affect renewable energy performance in high-income resource-based economies (Hunady et al., 2025).

This study adds a new addition to the energy transition literature by examining the use of solar energy in Australia, which is a high-income, fossil-fuel-exporting country and has been similarly under-researched on this front. While other studies have generally focused on either developed economies or developing countries, relatively few of these have explored solar adoption in resourceful economies that fall between the two categories, such as is the position with Australia (Graham et al., 2021). By doing so, the study bridges a significant gap in the literature by investigating the understudied role of financial globalization in shaping solar energy transitions in natural resource-dependent settings (Burke and Stephens, 2018). Besides, it offers an in-depth analytical framework that unites the demand-side drivers (e.g., population growth and economic development) alongside the supply-side drivers (e.g., energy infrastructure and capital flows), increasing the methodological enrichment of empirical analysis in this area (Rai and Robinson, 2015). By situating Australia within the broader global energy context, the study expands current knowledge on how structural and financial considerations compound in shaping renewable energy adoption (Simshauser, 2018). Looking only at the period between 1991 and 2023, the analysis can encompass Australia's full evolution from low renewable penetration to its current position as a global leader in solar energy, with longitudinal gains that cross-sectional analyses often lack (Steffen et al., 2019).

The remainder of this paper is structured as follows: Section 2 reviews the relevant literature on the impact of the independent variables on solar energy consumption. Section 3 outlines the model and methodology used in the analysis. Section 4 presents and discusses the empirical results, and Section 5 concludes the paper.

2. LITERATURE REVIEW

The transition to solar energy has emerged as a major decarbonization pathway worldwide, but empirical studies that directly address consumption of solar energy (SEC) are oddly limited compared to analyses of overall renewable energy. This review synthesizes global evidence relating to the determinants of SEC, contrasting cross-national evidence from developed and developing countries with particular regard to Australia's singular position as a wealthy developed nation. The analysis reflects significant heterogeneity in how economic, environmental, and institutional factors affect solar adoption across different national contexts.

2. 1. CO_2 EMISSIONS AND SOLAR ADOPTION

The relationship between CO_2 emissions and solar energy consumption (SEC) is extremely diverse in different economic settings. In Europe, Carley et al. (2018) confirmed that the countries with more aggressive climate policy reforms had greater levels of solar adoption, reflecting policy-oriented correlations between emissions and renewable transformations. Empirical evidence from the United States by Jeon (2022) revealed complex dynamics in which state-level differences in carbon pricing mechanisms led to divergent SEC growth patterns despite the convergence of emission reduction objectives (Idris and Razak, 2025). Derouez (2025) illustrates how rising emissions are inducing policy transitions to solar production in fossil fuel economies, giving useful analogies to the Australian case. Shrimali and Kniefel (2011), however, find less strong emissions–solar relationships in India due to inconsistent policy implementation and competing development agendas. The two cases together indicate how institutional readiness is a mediator of the impact of emissions on the uptake of solar technology in different national contexts. Thus, we proposed the first hypothesis:

H_1: There is a positive relationship between CO_2 emissions and solar energy consumption Australia.

2. 2. FOSSIL FUEL DEPENDENCE AND SOLAR TRANSITION

Empirical evidence consistently shows that over-reliance on coal (or fossil fuels) tends to discourage the adoption and use of solar energy, both directly due to competition and indirectly by disrupting policy and investment frameworks for renewables. In India, Karlilar and Emir (2023) employed a Fourier ADL cointegration technique and found a long-run negative cointegration among the consumption of coal and solar power, demonstrating that increased coal consumption suppresses the consumption of solar. The same dynamics apply to the US commercial sector, as wavelet and quantile regression analysis indicate a positive short-term relationship but a long-term negative one, while fossil fuel consumption decreases, renewable consumption (solar included) increases (Singh et al., 2022).

Hybrid energy system research emphasizes the technology and cost competition between solar and coal. Serrano-Sanchez et al. (2019) assess a hybrid solar-coal power plant and report that the supremacy of coal inhibits solar integration growth, accounting for the higher capacity factor and price of coal in current grids. Contrariwise, Vardar et al. (2022) emphasize that subsidies to coal and other fossil fuels diminish policy support for alternatives like rooftop solar, leading to slower growth in solar installations.

Local case studies also validate the trend. In China, investment in coal-fired infrastructure continues to crowd out investment in large-scale solar PV schemes even as the country added solar capacity (Luo et al., 2024). Likewise, Turkey's solar decline since 2018 was concurrent with renewed subsidies on coal plants and exchange rate pressures that facilitated fossil investments (Vardar et al., 2022). Thus, we proposed the second hypothesis:

H_2: Coal consumption has a negative effect on solar energy consumption in Australia.

2. 3. ECONOMIC GROWTH AND SOLAR ENERGY

It is a significant factor in the trend of adoption of renewable energy sources, like solar energy. There is a general agreement within the literature that higher GDP levels provide for greater investment in clean technology, but the magnitude and the nature of this relationship may vary depending on the context. Hechmi (2025), utilizing the application of FMOLS and CCR estimators, confirms a long-run positive relationship between GDP and renewable energy consumption in Southeast Asia and explains the means by which economic growth strengthens institutional and financial capacities for clean energy transformations. Tudor and Sova (2021) confirm, in the same context, that GDP per capita significantly increases renewable energy consumption for an international sample, attributing the effect to increasing environmental awareness and stronger demand for new-generation infrastructure.

However, the effect of GDP is not equally strong in all environments. Darvishi and Varedi (2018), investigating developed countries by employing dynamic panel methods, note that while GDP boosts the use of renewable energy in both the short run and long run, it hinges on national energy system development and policy mechanisms. Li (2024) closer aligns this view, proving that GDP could be insufficient for the overall acceptance of solar if not supplemented with targeted incentives and local technology readiness.

Combined, these studies suggest that while economic development is a pre-requisite facilitator of solar energy expansion, its role is boosted or constrained by policy structure, innovation systems, and the quality of institutions. This emphasizes the need to view GDP less as a standalone driver, but as part of a wider facilitating environment for renewable energy transition. Thus, we proposed the third hypothesis:

H_3: Economic growth has a positive impact on solar energy consumption in Australia.

2. 4. POPULATION GROWTH AND SOLAR ENERGY CONSUMPTION

Most current research that investigates the interaction between population growth and consumption of clean energy targets renewable energy more generally than solar electricity in particular. The broad focus, although revealing, is missing in explaining how population dynamics specifically determine the adoption of solar technology, which carries unique infrastructural and policy demands.

D.H.Vo and A.T.Vo (2021) examined the effect of population growth on the consumption of renewable energy in Southeast Asian countries using panel data. The evidence from the study is a statistically positive relationship between population growth and the consumption of renewable energy. The findings show that an increasing population leads to higher energy consumption, which in turn encourages the use of renewable energy sources to enable sustainable development goals.

Yang et al. (2016) treated China comprehensively and analyzed the impact of urbanization, a population process in nature, on renewable energy consumption. Through their empirical evidence, they found that urbanization has a positive influence on renewable energy consumption. The authors assign this to increased levels of energy consumption within growing cities and the impact of stricter environmental policies, which, as a response to abrupt population shifts, guarantee a transition to cleaner alternatives for energy consumption.

Derouez (2025), while primarily focusing on technological advancement and economic growth, also considered population growth as a parameter that influences solar electricity production in Saudi Arabia. The results indicate that population growth has a positive long-term impact on solar electricity production. This is because mounting population pressures contribute to the demand for electricity, compelling national energy policies towards expandable and clean energy sources like solar to ensure energy security and reduce hydrocarbon dependence (Nurgaliuly and Smagulova, 2025).

All these findings as a whole identify the necessity to coordinate demographic change and energy planning to render the energy transition sustainable. Thus, we proposed the fourth hypothesis:

H_4: Population growth has a negative effect on solar energy consumption in Australia.

2. 5. FINANCIAL GLOBALIZATION AND SOLAR ENERGY CONSUMPTION

The connection between the use of renewable energy and financial globalization has attracted increasing scholarly attention, with most studies addressing the industry at large and neglecting solar energy specifically (Ruslan et al., 2025). Financial growth, capital market openness, and capital flows across borders are widely recognized as potential drivers of clean energy adoption. Wu and Broadstock (2015) characterize that better financial systems ease capital shortages, which encourage renewable energy investment in emerging economies. Similarly, Wang et al. (2023) and Sun et al. (2023) discover that financial development positively affects the adoption of renewable energy, particularly in institutions that ensure investor confidence and market stability.

Majeed et al. (2022) also show how economic globalization and the rise in environmental innovation and energy efficiency can be very effective in promoting the use of renewable energy. They, however, like the majority of literature available, do not control for solar energy alone, thereby neglecting the unique technology and investment character of the subsector. Furthermore, recent research suggests emphasis on emerging economies or developed industrial nations with less attention to middle-ground energy resource countries like Australia, where financial openness might operate differently with domestic energy channels. Thus, we proposed the fifth hypothesis:

H_5: Financial globalization has a negative impact on solar energy consumption in Australia.

This study addresses this gap by focusing exclusively on solar consumption and examining how the international economic integration of finance, alongside environmental and economic determinants, shapes solar investment in a high-income, energy-exporting country. Doing so, it sheds new light on how the international integration of capital influences clean transitions in advanced economic settings.

3. MODEL AND METHODOLOGY

3. 1. THE MODEL

This study explores the determinants of solar energy consumption in Australia during the period 1991-2023, using the variables of CO_2 emissions, coal consumption, economic growth, population growth, and financial globalization. These parameters are chosen because of their theoretical relevance to the energy transition dynamics. CO_2 emissions, and coal consumption measure Australia's dependence on fossil fuels, while GDP indicates the economic capacity to invest in renewables, population growth represents energy demand drivers, and financial globalization captures international capital flows for the diffusion of clean energy. Thus, the basic functional model can be expressed as (eq (1)):

$$SE = f\,(CO2,\ COAL,\ GDP,\ POP,\ FG) \qquad (1)$$

Where SE represents the solar energy consumption per capita (measured in kilowatt-hours of primary energy per person, using the substitution method); CO2 denotes total carbon dioxide emissions (Mt CO2e); COAL refers to Coal consumption per capita (measured in kilowatt-hours per person); GDP is gross domestic product per capita (Constant 2015 US$); POP indicates the Population growth (annual %); and FG captures the financial globalization (KOF financial globalization data takes values between 0 and 100). Reputable sources were used to gather the annual data, including Our World in Data, the World Development Indicators (WDI), and the KOF Swiss Economic Institute.

This study analyzes both short- and long-term effects using the autoregressive distributed lag (ARDL) technique. A natural logarithmic linear form of the empirical model is shown below.

(2)

(eq (2)):

$$LnSE_t = \alpha_0 + \alpha_1 CO2_t + \alpha_2 COAL_t + \alpha_3 GDP_t + \alpha_4 POP_t + \alpha_5 FG_t + \varepsilon_t \quad (2)$$

Here, α_0 is the constant term, α_1 to α_5 denote the long-run elasticities of the respective explanatory variables. The logarithmic transformation of variables allows for direct interpretation of coefficients as percentage changes, making it straightforward to assess how each factor proportionally influences solar energy adoption per capita. The ARDL framework is useful for small sample sizes and mixed order integration; hence, the ARDL specification is well-suited for examining Australia's solar energy transition dynamics during the study period.

3. 2. ESTIMATION METHOD

We apply the Autoregressive Distributed Lag (ARDL) bounds testing procedure to explore the long-run associations between solar energy diffusion and its drivers in Australia. The ARDL has several distinct advantages, which make it particularly apt for the present study. It's more flexible in comparison to standard cointegration concepts; for instance, it allows for different orders of integration, and it is robust to small sample sizes. This double role of the approach for modeling both short-term dynamics and long-term equilibrium relationships gives a complete view of the transition of Australia towards solar energy (Pesaran et al., 2001). It is these attributes of the ARDL methodology that lend it particular relevance for the 1991-2023 period, where economic, environmental, and energy policy forces interplay to form patterns of solar adoption. The general form of our ARDL model is specified as (eq (3)):

$$\begin{aligned}\Delta LnSE_t = {} & \alpha_0 + \lambda_1 LnSE_{t-1} + \lambda_2 LnCO2_{t-1} + \lambda_3 LnCOAL_{t-1} + \lambda_4 LnGDP_{t-1} \\ & + \lambda_5 LnPOP_{t-1} + \lambda_6 LnFG_{t-1} + \sum_{k=1}^{n} \alpha_1 \Delta LnSE_{t-k} + \sum_{k=1}^{n} \alpha_2 \Delta LnCO2_{t-k} \\ & + \sum_{k=1}^{n} \alpha_3 \Delta LnCOAL_{t-k} + \sum_{k=1}^{n} \alpha_4 \Delta LnGDP_{t-k} + \sum_{k=1}^{n} \alpha_5 \Delta LnPOP_{t-k} \\ & + \sum_{k=1}^{n} \alpha_6 \Delta LnFG_{t-k} + \varepsilon_t\end{aligned} \quad (3)$$

Where Δ represents the first difference, the short-run coefficients are denoted by α_1 through α_2, and the long-run coefficients by λ_1 through λ_2.

There are two steps involved in the estimating process. The first step is to use the limits testing approach to check for cointegration (Pesaran et al., 2001). There is no long-term association (H_0: $\lambda_1 = \lambda_2 = \lambda_3 = \lambda_4 = \lambda_5 = \lambda_6 = 0$) versus the alternative of cointegration, according to the null hypothesis. The bounds test determines whether a long-run equilibrium exists. In this case, the null hypothesis (H_0) is that such a relationship does not exist—i.e., adoption of solar energy is not related to CO_2 emissions, coal consumption, GDP, population growth, or financial globalization in the long run. Rejecting H_0 suggests that such factors as a group influence solar adoption, short-run imbalances that correct over time. In order to determine whether cointegration exists, the F-statistic was compared to the critical values of the bounds; if it was below the lower bounds, we concluded that there is no long-term relationship; if it falls between the bounds, the result is inconclusive (Solaymani, 2022).

The optimal lag length of the Autoregressive Distributed Lag (ARDL) model was established with the use of Akaike Information Criterion (AIC) due to its better performance in finite samples and ability to reconcile model fit with parsimony. Compared to the Schwarz Criterion

(SC) or Hannan-Quinn (HQ), which both have the risk of over-penalty of lag length for small samples (Lütkepohl, 2005), AIC does not face the risk of underfitting - a critical concern for Australia's energy transition, as policy and market responses have lagged effects (Pesaran et al., 2001). This approach has a strong identification of short-run dynamics while maintaining statistical efficiency. Once the presence of cointegration has been established, we estimate the error correction model (ECM) using eq (4):

$$\Delta LnSE_t = \alpha_0 + \sum_{k=1}^{n} \alpha_1 \Delta LnSE_{t-k} + \sum_{k=1}^{n} \alpha_2 \Delta LnCO2_{t-k} + \sum_{k=1}^{n} \alpha_3 \Delta LnCOAL_{t-k} + \sum_{k=1}^{n} \alpha_4 \Delta LnGDP_{t-k} + \sum_{k=1}^{n} \alpha_5 \Delta LnPOP_{t-k} + \sum_{k=1}^{n} \alpha_6 \Delta LnFG_{t-k} + \emptyset ECM_{t-1} + \varepsilon_t \tag{4}$$

Where $\emptyset$ represents the speed of adjustment coefficient and ECM_{t-1} is the error correction term lagged by one period.

Post-estimation diagnostic tests were conducted once more for the sake of determining the adequacy of the model. This included normality of the residuals, serial correlation, and heteroskedasticity tests. The stability of the model was assessed via the cumulative sum (CUSUM) and cumulative sum of squares (CUSUMSQ) statistical tests, as suggested by Brown et al. (1975). The ARDL model is appropriate for our analysis because of its ability to support variables with various integration orders, and it is potentially more suitable for small sample sizes.

The long- and short-run coefficients of the variables in the model are examined using the ARDL bounds testing technique, but it doesn't reveal how each variable reacts to shocks from other variables or how long these responses last over time. To solve this, the study estimates the dynamic effects of such shocks using the generalized impulse response approach, which was first presented by Koop et al. (1996) and Pesaran and Shin (1998).

To ensure the robustness of our ARDL model estimates, we apply three additional cointegration techniques as sensitivity tests: Dynamic Ordinary Least Squares (DOLS), Fully Modified Ordinary Least Squares (FMOLS), and Canonical Cointegrating Regression (CCR). They account for potential shortcomings of the ARDL model by employing different estimations of long-run relations that are endogenous, serial correlation, and non-normality robust (Saikkonen, 1991; Phillips and Hansen, 1990; Park, 1992). The DOLS approach uses leads and lags of first-differenced regressors to correct for endogeneity, while FMOLS corrects least squares for serial correlation and endogeneity in variables that are nonstationary. CCR realigns variables into asymptotic efficiency without changing standard methods of inference. By performing a comparison between these methods, we affirm whether the relations between solar adoption and its determinants are consistent across different estimation assumptions, thereby raising confidence with respect to our results. This multiple method framework is particularly relevant given Australia's complex energy transition environment, where structural breaks and shifting orders of integration may destabilize parameters.

4. RESULTS AND DISCUSSION

4. 1. DESCRIPTIVE STATISTICS

Table 1 presents the descriptive statistics of the variables.

Table1. Descriptive Statistics

Variable	Obs.	Mean	Std. Dev.	Min	Max
LnSE	33	3.948	2.669	-0.069	8.394
LnCO2	33	2.853	0.088	2.640	2.957
LnCOAL	33	10.146	0.211	9.671	10.380
LnGDP	33	10.813	0.164	10.492	11.028
LnPOP	33	0.232	0.457	-1.960	0.895
LnFG	33	4.297	0.070	4.122	4.378

Source: Eviews12 output based on authors' computation

The descriptive statistics (Table 1) for Australia's variables based on our 33 observations show significant patterns. LnSE (solar energy per capita) has the broadest range and a standard deviation of 2.669, indicating considerable movement within this renewable energy metric (observed areas fluctuate from -0.069 to 8.394). LnCO2 (CO_2 emission per capita) shows a standard deviation of .088 with a limited range, indicating a consistent energy consumption pattern among fossil fuels, including coal and gas. While both LnGDP (GDP per capita) and LnFG (an indicator of financial globalization) have little variation (with standard deviations of 0.164 and 0.070, respectively), this suggests that Australia's economic patterns may have been stable during the period of analysis, thus stabilizing energy consumption on coal and gas. In contrast, LnPOP (Population) has a standard deviation of 0.457, suggesting variation in population change, which is somewhat surprising given that the observed areas represent a "per capita" measure. Thus, we would expect population growth to be relatively smooth. Nevertheless, this more extensive standard deviation emphasizes Australia's relatively slow transition of its energy systems, as we observe substantial solar growth still paired with strong reliance on fossil fuels.

4. 2. UNIT ROOT TEST

Unit root tests such as Augmented Dickey-Fuller (ADF) and Phillips-Perron (PP) tests are critical in time series analysis to monitor model selection for the sake of avoiding spurious regressions. These tests are able to determine either variable stationarity or the order of integration, which is a critical factor in determining econometric models in various fashions, such as ARDL and error correction models, as well as correctly measuring long-run relationships and improving forecasting. The unit root test results are reported in Table 2.

Table 2. The results of the unit root test

Variable	ADF		PP		Remarks
	Level	1st Diff.	Level	1st Diff.	
	Prob.	Prob.	Prob.	Prob.	
LnSE	0.9000	0.0517*	0.8005	0.0425**	I(1)
LnCO2	0.9978	0.0011***	0.9976	0.0011***	I(1)
LnCOAL	0.9731	0.0312**	0.9670	0.0328**	I(1)
LnGDP	0.9549	0.0001***	0.9545	0.0001***	I(1)
LnPOP	0.0095***	0.0000***	0.0117**	0.0000***	I(1)
LnFG	0.2601	0.0000***	0.3018	0.0000***	I(1)

Note: **, and *** indicate 5% and 1% significance levels, respectively

Source: Eviews12 output based on author's computations

As presented in Table 2, the ADF and PP unit root tests indicate uniformly that all variables, which are LnSE, LnCO2, LnCOAL, LnGDP, LnPOP, and LnFG, are integrated of order one, I(1). While all variables are largely non-stationary at their levels (other than the LnPOP variable, which is demonstrated to contain some level stationarity but is also deemed to be I(1)), they establish stationarity upon being taken to the first difference with statistically significant probability values. The finding that all the variables are I(1), i.e., they are made stationary after first-differencing, has two important implications for our study. First, it reveals that the variables have stochastic trends (i.e., they trend randomly over time due to random shocks), which is common in macroeconomic and energy data. Secondly, the I(1) property supports our use of the ARDL bounds testing approach since it accommodates variables that are rendered stationary after differencing without resulting in spurious regression results (Pesaran et al., 2001). From a policy viewpoint, this suggests Australia's solar take-up and its determinants change cumulatively with time, and that shocks in the past have persistent effects unless policy intervention tends to violate these patterns.

4. 3. DETERMINING THE OPTIMAL LAG STRUCTURE IN THE ARDL MODEL

The lag order selection results from the ARDL model evaluations associated with Table 3 are summarized in this section. The Akaike Information Criterion (AIC) suggests lag 2 as the most appropriate lag specification for Australia's solar energy, CO_2 emissions, GDP, financial globalization, coal consumption, and population growth, with a notably superior AIC value of -22.4829. Although the AIC is the preferred criterion for lag order, all the other lag order selection measures coincide with lag 2 when assessed for relative improvements, since other measures point to lag 2 as the optimal lag order, with no adverse identifications. For example, lag 2 had a comparable outcome based on the Hannan-Quinn Criterion (HQ), of -21.3067, while the Final Prediction Error (FPE) reaches its minimum (9.65e-18) at this lag length.

Thus, we determined to report the results from the ARDL(2,2,0,2,0,2) estimation based on two lags each for solar energy (LnSE), CO_2 emissions (LnCO2), GDP (LnGDP), and financial globalization (LnFG), and on the other hand, did not include a lagged term for coal consumption (LnCOAL) or population growth (LnPOP). The lack of lagged impacts for coal consumption (LnCOAL) and population growth (LnPOP) implies that their impacts on solar adoption are largely contemporaneous. In the case of LnCOAL, this implies immediate coal-to-solar substitution in Australia's electricity market because of immediate policy responses (e.g., renewable energy targets). In the case of LnPOP, it suggests instant adjustments in energy demand by new residential builds equipped with solar systems upfront. Since the ARDL(2,2,0,2,0,2) represents an optimal model with respect to fit versus parsimony, and successfully captures the dynamic relationships displayed by the rates of solar energy adoption in Australia, a 2-lag approach is well positioned to analyse the effect of the implementation of policy directives or the manifestations of market rationalization, all of which will usually exhibit lagged impacts in energy transitions.

Table 3. Lag selection

Lag	LogL	LR	FPE	AIC	SC	HQ
0	171.1453		9.51e-13	-10.6545	-10.3770	-10.5641
1	377.3432	319.2743	1.70e-17	-21.6351	-19.6922*	-21.0017
2	426.4843	57.0671*	9.65e-18*	-22.4829*	-18.8748	-21.3067*

* indicates lag order selected by the criterion. LR: sequential modified LR test statistic (each test at 5% level); FPE: Final prediction error; AIC: Akaike information criterion; SC: Schwarz information criterion; HQ: Hannan– Quinn information criterion

Source: Eviews12 output based on author's computations

4. 4. ARDL BOUND TEST

Table 4 lays out the results from the bounds test. This test enables us to confirm the presence of cointegration among the variables while also estimating the short-run dynamics and long-run equilibrium relationships.

Table 4. ARDL F-Bound test for cointegration

F-Bound Test	Null Hypothesis: No levels of relationship			
ARDL Lag model	(2,2,0,2,0,2)			
Test statistic	Value	Significance level	I(0)	I(1)
F-statistic	5.720045	10%	2.08	3
K	5	5%	2.39	3.38
		2.5%	2.7	3.73
		1%	3.06	4.15

Source: Eviews12 output based on author's computations

ARDL bounds test provides two sets of critical values: I(0) for variables that are stationary and I(1) for unit-root variables. These provide a decision boundary for cointegration testing. When the F-statistic calculated intersects the I(1) upper bound (4.15 at 1% significance in our case), we reject the null hypothesis of no cointegration, confirming a long-run relationship exists. Conversely, values less than the I(0) lower bound (3.06) indicate no cointegration, while those between the bounds are inconclusive (Pesaran et al., 2001). As shown in Table 4, the variables have a stable long-term cointegration relationship, as evidenced by the F-statistic of 5.720, which is higher than the upper critical bound (4.15 at 1% significance). This shows that during the studied period, Australia's solar energy adoption (LnSE) maintained an equilibrium relationship with CO_2 emissions, coal consumption, GDP, population growth, and financial globalization.

4. 5. LONG-RUN AND SHORT-RUN ANALYSIS OF THE ARDL MODEL

The findings of the ARDL model are given in Table 5.

Table 5. Long run and short run elasticities

Dependent variable: LnSE			
Variable	Coeff.	t-stat.	Prob.
Long –run coefficients			
LnCO2	8.280**	3.304	0.023
LnCOAL	-0.822***	-5.147	0.000
LnGDP	18.297***	3.483	0.000
LnPOP	-0.429**	-2.697	0.015
LnFG	-18.851***	-3.081	0.007
C	-46.709*	-2.053	0.056
Short-run coefficients			
D(LnSE(-1))	0.587***	6.684	0.000
D(LnCO2)	10.216***	5.270	0.000
D(LnCO2(-1))	4.688**	2.801	0.012
D(LnGDP)	-6.809***	-3.005	0.008
D(LnGDP(-1))	6.970***	3.622	0.002
D(LnFG)	-2.529**	-2.369	0.030
D(LnFG(-1))	4.421***	3.595	0.002
CointEq(-1)	-0.530***	-7.360	0.000
R-Square	0.7932		
AdjustedR^2	0.7303		

Note: *, ** and *** indicate 10%, 5% and 1% significance levels, respectively.

Source: Eviews12 output based on author's computations

The long-run ARDL estimates in Table 5 exhibit statistically significant ($p < 0.05/0.01$) solar adoption determinants in Australia: CO_2 emissions (8.280) and GDP (18.297) are positively elastic, while solar deployment rises with both climate policy pressures and economic growth, and coal consumption (-0.822) shows plain fossil fuel substitution. The negative population effect (-0.429) reveals metropolitan housing limitations restrain per capita adoption despite increasing demand, and the significant negative effect of financial globalization (-18.851) reveals previous capital flows favoring fossil investments over renewables and highlights structural barriers in Australia's energy transition.

In regard to the short run, we have a better opportunity to look at immediate adjustments. The CO2 emissions increased immediately after the lagged period of solar energy incursion (D(LnSE(-1))), which had a coefficient of 0.587, and then after that, the adjustments to emissions attributable to carbon dioxide emissions (D(LnCO2)) were even higher (10.216). Similarly, the growth of GDP had the following short-run negative coefficient (-6.809), then compensated for with a positive rebound in the later period of (+6.970). Also, Financial Globalization had the same mixed effects with a 1st order short-run decrease (-2.529), then a compound surge into the longer term future thereof to 4.421 lag period.

Cointegration efforts continued after completing 1st differences, due to the moderate degree of non-stationarity of those variables, with the appropriate sum of coefficients with a 0.530 coefficient indicating a rather large annual 53% adjustment of the deviation towards the estimated long-run equilibrium relationship.

According to the estimation results of both short-run and long-run coefficients in the ARDL model, evidence validates all five hypotheses derived from the literature review. Specifically, evidence verifies that CO_2 emissions and economic growth positively influence solar energy consumption and that population growth and coal consumption negatively influence them. Additionally, financial globalization statistically significantly affects as theoretical expectations imply. These results validate the conceptual model constructed in the foregoing sections and demonstrate significant empirical support for hypothesized relationships.

4. 6. DIAGNOSTIC TESTS

In order to verify the strength and reliability of ARDL outputs, we performed a battery of diagnostic tests. These tests review principal statistical assumptions such as normality of the residual, autocorrelation, heteroskedasticity, and model stability. By checking these conditions, we verify that the estimated relationships are statistically sound and that they are not biased by major specification errors. These statistical tests make certain that our model's results are reliable for policy analysis. The tests are "quality checks"; the Breusch-Godfrey test confirms that results aren't distorted by hidden patterns in the data, and the ARCH test ensures there is no volatility clustering in the results. The Jarque-Bera test indicates that the error distribution is normal (a symmetrical bell curve), so standard statistical interpretations apply. Finally, the Ramsey RESET is a "specification detector," which reassures that there aren't omitted significant variables or misspecified relationships. These diagnostic checks are reported in Table 6, accompanying the high credibility of our estimates concerning the long-run and short-run dynamics of solar power take-up in Australia.

Table 6. Outcomes of stability and diagnostic testing

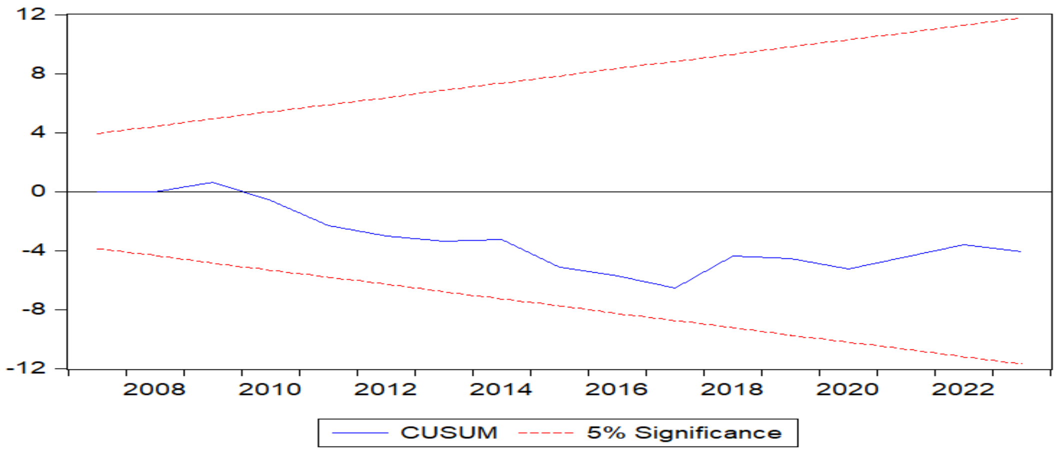
Diagnostic test	Coeff.	Prob.	Outcomes
Breusch-Godfrey Serial Correlation LM Test	0.511	0.610	No serial correlation exists
ARCH	0.117	0.734	No heteroscedasticity exists
Jarque-Bera	0.427	0.808	Residuals are normally distributed
Ramsey RESET Test	1.223	0.239	Model is correctly specified

Source: Eviews 12 output based on author's computations

The results of the diagnostic test confirm the statistical reliability and stability of the ARDL model. The Breusch-Godfrey Serial Correlation LM Test (p = 0.610) indicates no autocorrelation of residuals, thus satisfying the assumption of independent error terms. Similarly, the ARCH test (p = 0.734) eliminates heteroskedasticity, yielding constant variance among residuals. The Jarque-Bera statistic (p = 0.808) confirms that the residuals are normally distributed and therefore makes inference statistics reliable. Finally, the Ramsey RESET statistic (p = 0.239) shows there are no omitted variables or misspecification of functional form, assuring correct model specification. Altogether, the findings from above reveal the ARDL estimates to be reliable in studying the solar energy adoption dynamics for Australia.

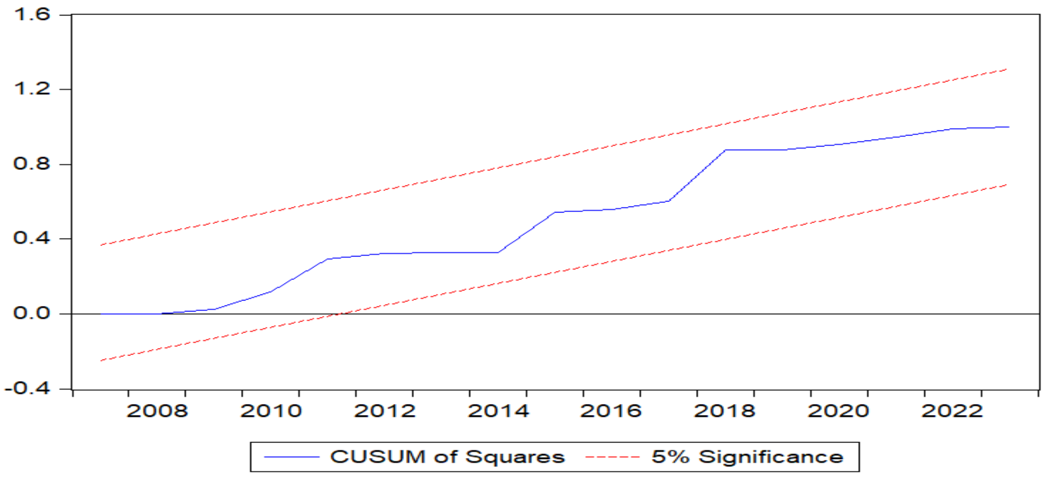
Figures 1 and 2 show that the CUSUM and CUSUM of Squares plots remain within the 5% significance bounds (indicated by the red dashed lines), confirming the stability of the model parameters.

Figure1. CUSUM plot for coefficients' stability of ARDL model at 5% level of significance



Source: Eviews 12 output based on author's computations

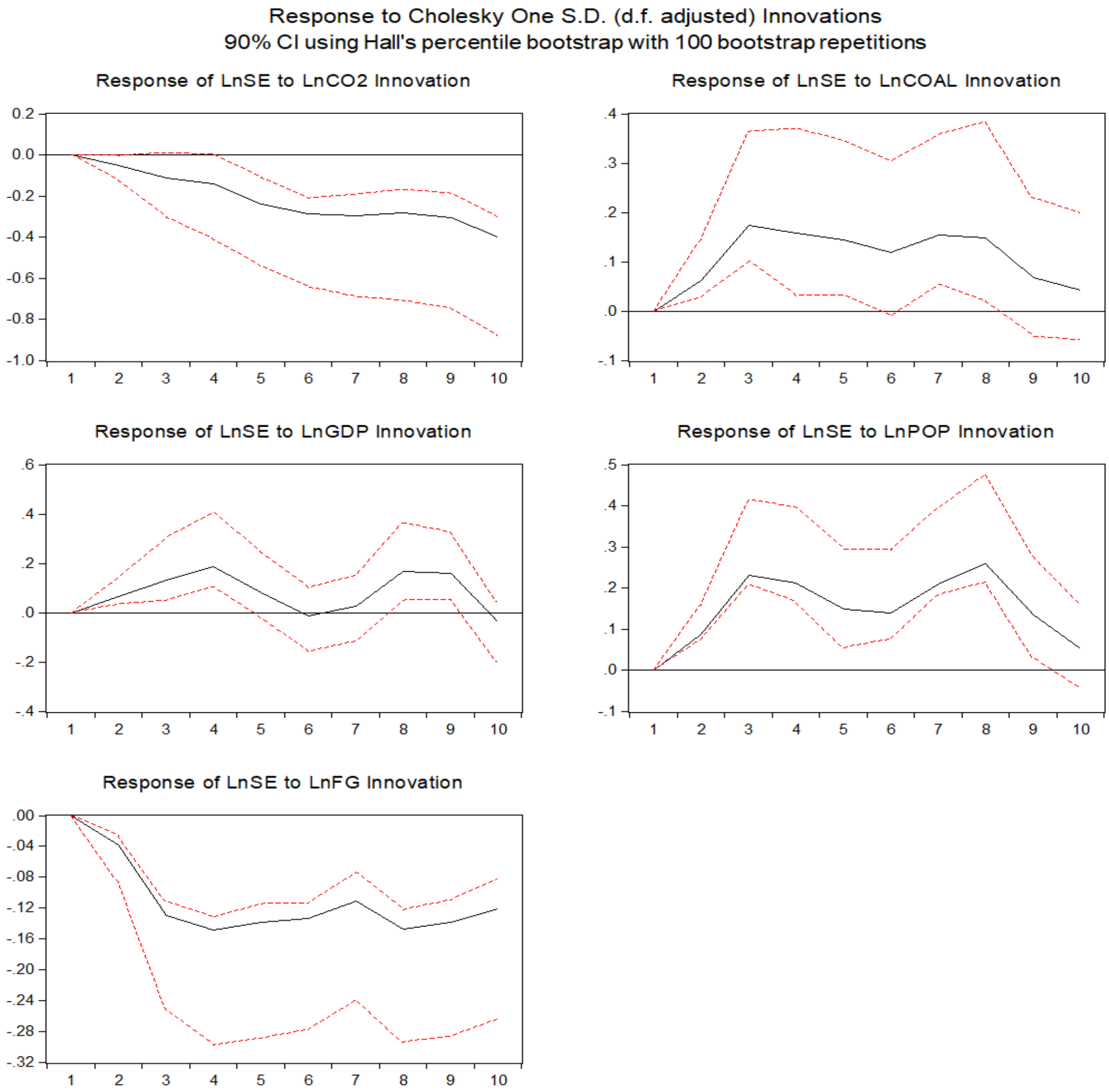
Figure2. CUSUMSQ plot for coefficients' stability of ARDL model at 5% level of significance



Source: Eviews12 output based on author's computations

4. 7. IMPULSE RESPONSE RESULTS

Figure3. Impact of one standard deviation shock to all variables on SEC.



Source: Eviews12 output based on author's computations

The Impulse Response Functions (IRFs), as shown in Figure 3, provide the dynamic perspective that complements the static elasticities of the ARDL model. While the ARDL estimation shows long-run positive effects of CO2 and GDP on solar energy (LnSE) and negative effects of coal and fossil fuels, the IRFs reveal the way these effects evolve. For instance, LnCO2 shock likely leads to a permanent and instantaneous increase in LnSE in line with the ARDL's long-run coefficient that is positive, suggesting that higher emissions spur the take-up of solar, possibly as a policy response. Similarly, LnSE's adverse response to LnCOAL and LnFG innovations in the IRFs is in line with the ARDL's evidence for substitution effects. However, the IRFs also convey short-run shocks or lags behind and overshooting in responses that the short-run ARDL coefficients only reflect partially (e.g., the GDP fixed effects). This "overshooting" pattern (i.e., the initial spike in LnGDP beyond its long-run impact) happens when solar adoption is more sensitive to shocks in the short run than would be implied by its ultimate equilibrium. This trajectory is similar to that of an overcorrection in markets, i.e., when growth takes off (positive GDP shock), households and utilities may invest in solar installations at unsustainable rates, with gradual stabilization afterward as supply chains and policies catch up. Such overshooting is characteristic of energy transitions where investment lags (e.g., in grid infrastructure) create temporary imbalances between additions of renewable capacity and the absorption capacity of the system (Kilian and Vigfusson, 2011). Overall, the IRFs replicate the directional findings of the ARDL but add temporal specificity by showing that solar power adoption is not only responsive immediately to shocks but also subject to longer-run equilibrium adjustments.

4. 8. ROBUSTNESS CHECKS

To ensure the stability of our econometric findings, we employ alternative estimation techniques like FMOLS (Fully Modified Ordinary Least Squares) which corrects for statistical biases in nonstationary data, DOLS (Dynamic Ordinary Least Squares) designed for small samples with mixed trends, and CCR (Canonical Cointegrating Regression) which handles non-standard data distributions. These estimates allow us to check the consistency of our findings based on different model specifications, avoiding endogeneity and serial correlation issues. Findings based on these alternative approaches provide additional confirmation of the validity of our primary findings. Results of these techniques are presented in Table 7.

Table 7. The FMOLS, DOLS, CCR results

Dependent variable: LnSE			
Variable	FMOLS Coefficient, (t-Statistics), [p-Value]	DOLS Coefficient, (t-Statistics), [p-Value]	CCR Coefficient, (t-Statistics), [p-Value]
Long –run coefficients			
LnCO2	16.157 (6.126) [0.000]***	14.012 (4.854) [0.000]***	16.694 (5.353) [0.000]***
LnCOAL	-13.853 (-10.292) [0.000]***	-12.727 (-8.624) [0.000]***	-14.112 (-9.050) [0.000]***
LnGDP	6.839 (4.714) [0.000]***	7.195 (4.581) [0.000]***	6.892 (3.691) [0.001]***
LnPOP	-0.032 (-0.230) [0.767]	-0.072 (-0.620) [0.541]	-0.022 (-0.138) [0.892]
LnFG	-1.166 (-0.479) [0.636]	-0.376 (-0.148) [0.884]	-1.422 (-0.442) [0.662]
C	29.532 (2.024) [0.053]*	16.960 (1.049) [0.303]	31.134 (1.860) [0.074]*

Note: * and *** indicate 10% and 1% significance levels, respectively

Source: Eviews12 output based on author's computations

Our CCR, DOLS, and FMOLS tests of robustness yield very consistent conclusions that affirm our primary results from ARDL. All three methods confirm the same directional relationships: (1) solar absorption is positively affected by CO_2 emissions and economic growth, (2) coal consumption and financial globalization reflect negative coefficients, and (3) population growth has minimal impacts. While there are few differences in coefficient magnitudes, with FMOLS/CCR typically measuring slightly stronger effects for environmental variables, the policy implications and statistical significance stand firm by the estimation approach. Such methodology convergence lends support to the fact that Australia's solar shift is best understood through climatic pressures and economic resources, regardless of technique. The unambiguous convergence of four alternative estimation approaches (ARDL, FMOLS, DOLS, CCR) occasions unprecedented confidence within our results.

4. 9. DISCUSSION

The estimates from the empirical ARDL model provide critical information on the complex relationships governing solar energy uptake in Australia during the period 1991-2023. The evidence reveals apparent long-run equilibrium relationships and short-run adjustment mechanisms that reflect the individual energy policy situation, economy, and environment of Australia.

The long-term estimation indicates that CO_2 emissions per capita have a strongly significant positive effect on the consumption of solar energy. This finding is aligned with policy responses to climate change pressures by Australia, particularly following significant international agreements like the Paris Agreement and national policy like the RET scheme (Australian Government, 2023). The positive relationship shows that previous instances of rising emissions have elicited policy responses and pressure from the public for cleaner energy technologies to be used, driving solar adoption. This can be shown most clearly after 2010, when there was a solar boom in Australia despite remaining heavily reliant on coal-fired production (Clean Energy Council, 2022). Our results are consistent with those of Derouez (2025). The significant immediate positive impact of CO_2 emission shocks demonstrates how severe environmental stressors, like those that occurred during Australia's devastating 2019 bushfire season, can prompt quick policy responses and shifts in consumer behavior toward renewable energy (Steffen et al., 2019).

Coal consumption per capita suggests a high negative correlation with solar absorption over the long run, evidencing the energy substitutability effect in Australia's electricity market. It is a measure of the structural barrier to departing from coal in a resource-rich economy where coal has traditionally dominated both domestic energy production and export revenue (Graham et al., 2022). The negative coefficient demonstrates the institutional and economic inertia of Australia's coal-based energy system, particularly in states like New South Wales and Queensland, where coal generation and mining have been at the center of regional economies. However, recent market trends with accelerated coal plant retirements suggest this relationship is possibly transforming (AEMO, 2024). Our findings are consistent with those of Karlilar and Emir (2023).

GDP per capita is the one with the highest positive coefficient, which shows how economic prosperity facilitates renewable energy investments. This is in line with the Australian experience, whereby periods of strong economic growth have facilitated both household-level solar PV and utility-scale renewable investment (Burns and Mountain, 2021). The magnitude of this effect affirms the capital-intensive character of energy transitions and that economic stability has to be maintained to facilitate the deployment of renewable energy. Our results are similar to those of Darvishi and Varedi (2018) and Tudor and Sova (2021). The GDP increase had the negative short-run coefficient of (-6.809), preceded by a compensatory positive one in the latter period of (+6.970). This is similar to an overcorrection in markets, i.e., growth accelerates (positive GDP shock), and utility and household sectors may invest in solar installations at unsustainable rates, with stabilization creeping in later as supply chains and policies get up to speed. Such overshooting is common in energy transitions where investment lags (e.g., in grid infrastructure) cause temporary discrepancies between renewable capacity addition and the absorptive capacity of the system (Kilian and Vigfusson, 2011).

The negative population growth coefficient reflects an interesting paradox, which can be due to Australia's distinctive demographic trends. While population increase would generally increase energy needs, this negative correlation with solar uptake per capita could be due to several factors: population increase focused in denser urban settings less conducive to rooftop solar, delay in new stock of dwellings to incorporate solar systems, or migrant group demography with changing energy consumption patterns (Burke and Stephens, 2018). The effect of population growth on SEC reflects particular Australian characteristics of demographic-energy dynamics. The measure of the % annual population growth captures net migration and natality but not their spatial pattern, which is determinative because 86% of Australians live in urban areas (ABS, 2023), where there is a potential for rooftop solar that depends on housing density. Additionally, measurement per capita leads to rapid population growth, potentially temporarily undermining adoption statistics as total capacity increases, since solar capacity grew 800% across the period from 2009 to 2019 while per capita adoption only built more slowly (AEMO, 2024). This suggests the variable is capturing transitional disequilibrium in housing and energy infrastructure rather than a genuine long-term inverse relationship. Our results are consistent with those of Derouez (2025).

Financial globalization has a highly negative impact, whose interpretation must be treated carefully in an Australian context. The effect likely represents the longstanding dominance of fossil fuel investment over the cross-border business of Australia, particularly through liquefied natural gas (LNG) exports to Asia (Garnaut, 2021). The discovery confirms that hitherto, global capital integration has predominantly realigned Australia's fossil fuel economy rather than generating its renewable energy revolution, even though this trend is potentially changing with rising passion for green hydrogen and strategic minerals (Australian Government, 2023). The short-run effects of financial globalization (LNFG) on the usage of solar energy in Australia are a complex process. While the ARDL model at first shows a negative impact, it turns into a positive coefficient for the next period, demonstrating that financial globalization's effect takes place through channels with a lag. This pattern may account for how global capital flows first tend to favor entrenched fossil fuel investments before gradually tending towards clean energy projects (Garnaut, 2021). The high adjustment rate (53% per year) indicates that Australia's solar industry responds rapidly to such monetary inflows, yet the transition from traditional to clean investment appears to have a J-curve pattern, with initial crowding-out effects reversing to longer-term support for clean infrastructure (Australian Government Department of the Treasury, 2023).

The short-run dynamics also reveal some important nuances of Australia's energy transition. The big error-correction term reflects quite rapid convergence to equilibrium, with about 53% of any disequilibrium being removed annually. This rapid rate of adjustment reflects the responsiveness of the Australian energy market to policy shocks and technological change, as evidenced in the dramatic uptake of rooftop solar following feed-in tariffs in the late 2000s (Nelson et al., 2025). The highly significant positive effect of lagged adoption of solar indicates the reinforcement effect of renewable energy deployment through learning curves, economies of scale, and social diffusion effects (Rai and Robinson, 2015).

5. CONCLUSION

The study aimed to empirically analyze determinants of solar energy adoption in Australia from 1991 to 2023 and establish long-run equilibrium relationships as well as short-run adjustment processes through ARDL modeling. The results indicate that solar energy deployment is greatly determined by CO_2 emissions, GDP growth, coal consumption, and financial globalization, with varied temporal effects that shape Australia's energy transition.

5. 1. RESEARCH LIMITATIONS AND FUTURE DIRECTIONS

While this study presents robust evidence about Australia's drivers of solar adoption, three constraints hold. First, the yearly frequency of data may hide the policy impacts observed in the short run by higher-frequency analysis. Second, the adverse role of financial globalization probably reflects historical fossil fuel investment dominance, not yet comprehensively explained by the KOF index. Third, national-level aggregation masks state-level dynamics, particularly between solar-pioneering states (e.g., South Australia) and coal-dependent territories. Quarterly data, the distinction between household vs. utility-scale solar uptake, and the inclusion of disaggregated financial flow indicators need to be employed in future studies to capture the energy transition's more fine-grained dynamics.

5. 2. POLICY IMPLICATIONS

Based on the findings of this research, certain policy and practical recommendations can be given to promote solar energy adoption in Australia. The use of coal has a particularly strong negative effect on solar adoption, meaning that persistent use of coal prevents solar capacity development. To address this, the government will need to hasten the retirement of coal-fired power plants, ideally by 2035, and reinforce Renewable Energy Zones by awarding them high-priority grid access and public funding. Where there are coal-dependent regions like New South Wales and Queensland, transition strategies and support for affected workers need to be implemented to enable the shift away from fossil fuels.

Financial globalisation today is leaning towards supporting investments in fossil fuel over renewable energy. This has to be reversed by establishing a clear Green Taxonomy that outlines approved clean energy investments and demands environmental disclosures from both domestic and foreign investors. All this would have to be complemented by providing tax breaks for foreign direct investment in solar projects, while discouraging fossil fuel-based investments by laying down certain penalties or increased reporting requirements.

Australia's economic growth has a very strong positive effect on solar energy adoption. This momentum needs to be channeled by investing a percentage of a country's GDP annually, say 2%, in solar research and development, grid modernization throughout the country, and expansion of community-based solar schemes. Solar power needs to be included in national infrastructure planning, with targeted tax incentives to create incentives for widespread industrial and commercial adoption.

Although population growth puts a negative long-term strain on per capita use of solar energy, this may be evidence of slower adoption in dense urban settings. To address this, urban development plans need to call for solar-ready construction of all new buildings. Incentives by the government need to subsidize solar incorporation into apartment buildings and multi-family housing. States need to establish solar adoption maps and identify high-growth areas with low solar penetration to address as a priority.

The study establishes that Australian solar power is responsive to market and policy signals quickly, with a projected 53% annual adjustment rate. The responsiveness must be leveraged by implementing adaptive tools such as dynamic feed-in tariffs, real-time net metering, and regular adjustments to solar procurement plans. A dedicated Solar Energy Rapid Response Task Force must be established in order to speed up permits, remove investment barriers, and be quick to act in response to global shifts in energy finance.

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