

Economic Feasibility Analysis of Renewable Energy Investment: A Cost-Benefit Model under Carbon Pricing Mechanisms

Junxi Zhuo*

College of Economics and Management, Shandong Agricultural University, Tai'an, 271018, China

*15269860183@163.com

Abstract

We build a cost-benefit model to assess the economic viability of renewable energy investment under carbon pricing mechanisms, drawing on 540 project-level observations from solar photovoltaic, onshore wind and offshore wind technologies in 30 jurisdictions over the period 2019 to 2024. The analytical approach integrates levelized cost of energy analysis with carbon-adjusted net present value estimation and includes technology-specific learning curves as well as carbon cost savings as a mediation pathway. Using baseline regressions with year and technology fixed effects, it is seen that an additional carbon price of 1 USD per metric ton of CO₂ equivalent is associated with a 4.32 USD/kilowatt increase in the project's net present value, which is found to be robust to various assumptions on the outcome measure and the discount rate between 5 and 9 percent. Carbon cost savings - the avoided emission costs compared with a fossil fuel generation baseline - are found to mediate the pricing effect using the Baron and Kenny approach by reducing the carbon price coefficient from 4.316 to 2.294. The technology heterogeneity is evident in the scenario analysis, when the carbon price is low (25 USD/Mt), medium (75 USD/Mt) and high (150 USD/Mt). Solar PV projects turn into positive NPVs in all three scenarios and have the highest marginal sensitivity of 5.82 USD/kW/USD\$ increase in carbon price, followed by onshore wind (4.16) and offshore wind (3.58). Due to the fact that offshore wind is more capital intensive than more mature technologies, a carbon price of over ~40USD/MT is required for it to become cost-competitive.

Keywords

Renewable Energy Investment; Carbon Pricing; Cost-benefit Analysis; Net Present Value; Levelized Cost of Energy; Carbon Cost Savings; Technology Heterogeneity.

1. Introduction

The worldwide shift toward low-carbon energy systems has moved renewable energy investment to the forefront of both climate policy and economic strategy. Carbon pricing mechanisms, among which emissions trading systems (ETS) and carbon taxes are the most common, are being adopted by a growing number of jurisdictions to internalize the external costs of greenhouse gas emissions and to steer capital toward cleaner technologies [1]. By 2024, more than 70 carbon pricing instruments had been put in place or formally scheduled across national and subnational governments, together covering close to 23 percent of global greenhouse gas emissions [2]. To both policymakers creating effective climate instruments and investors evaluating project returns over long time horizons, the impact of such pricing mechanisms on the profitability of renewables investments is evident.

A substantial body of international research has studied the link between carbon pricing and the deployment of renewables. Nordhaus [3] however showed that the optimal paths for carbon

pricing can significantly redirect investment portfolios in energy towards renewables by addressing market failures associated with carbon externalities. A general overview of the costs of mitigation of greenhouse gas emissions was provided by Gillingham and Stock [4], who found that the levelized cost of energy (LCOE) for solar and wind has dropped by over 85 percent in the last 10 years, thereby fundamentally altering the game. The LCOE of newly commissioned utility-scale solar PV projects was 0.049 USD per kWh in 2023, according to IRENA [5] (best fossil fuel LCOE in most parts of the world).

Concerning effectiveness of carbon pricing, Green [6] conducted a systematic analysis of ex-post studies and reported that carbon pricing instruments have, on average, reduced emissions by 5-21 percent below a counterfactual baseline. In a cross-country panel data analysis of the effectiveness of carbon pricing, Best et al. [7] concluded that the statistical significance of carbon pricing in reducing carbon intensity is strong in a variety of economic contexts. Rennert et al. [8] provided a new estimated range for the social cost of carbon of 185 USD/tm of CO₂, well above previous government estimates, suggesting that the prices in most jurisdictions are currently under the socially optimum levels.

The theory linking carbon pricing and renewable energy investment is sound. Acemoglu et al. [9] developed a directed technical change model that shows how environmental policy measures such as carbon taxation can spur the redirection of innovation from fossil fuel technology to cleaner technology if implemented early enough. Carbon pricing is an indispensable part of climate policy, but it is not enough in and of itself to achieve the comprehensive decarbonisation that is needed, and technology-specific support measures are required to complement it, argued Rosenbloom et al. [10]. Hepburn et al. [11] analyzed whether fiscal recovery packages speed up or retard the process of climate progress, and concluded that green investment multipliers are higher than conventional fiscal stimuli.

However, there are gaps in the existing knowledge on renewable energy investment economics in the context of carbon pricing. Many existing cost-benefit models also take carbon prices as a fixed exogenous parameter, and do not explicitly explore the impact of various pricing pathways on the viability of investments in technology types. Moreover, uncertainty about the carbon price has received little consideration in the context of technology-specific risk profiles in integrated analytical frameworks. However, there is still significant uncertainty surrounding damage functions and appropriate discount rates, which leads to a wide range of estimates of the social cost of carbon and results in wide divergence in optimal policy paths, as Tol [12] pointed out.

The World Bank [13] also highlighted the importance of price levels, coverage and design of complementary policies in the effectiveness of carbon pricing. Lazard [14] provided evidence that unsubsidised renewables are already at grid parity in some locations, which is taking the role of carbon pricing as more of an accelerator than a prerequisite for renewable deployment. Bistline and Blanford [15] explored the role of power in a net-zero energy system and noted that transition costs depend on when investments occur and on the mix of technologies.

In order to fill these gaps, we develop a cost-benefit model to measure the economics of renewable energy investment across various carbon price scenarios. It integrates LCOE estimation with net present value (NPV) modelling and brings in carbon cost adjustments, technology-specific learning curves, and takes into account the uneven impact of carbon pricing on different solar PV and onshore and offshore wind technologies, explicitly modelling the impact of carbon pricing price volatility and the uncertainty of policies on investment returns.

The rest of the paper goes like this. The conceptual definitions and theoretical foundations are presented in Section 2. The research design and the construction of the research model are described in Section 3. The empirical results are shown in section 4. The research conclusions are summarised and policy implications are drawn in Section 5.

2. Conceptual Definition and Theoretical Foundation

2.1. Definition of Core Concepts

2.1.1. Carbon Pricing Mechanism

Carbon Pricing Mechanism (CPM) refers to a policy measure which assigns a price to GHGs emissions and integrates external environmental costs of carbon-intensive activities into market transactions. The two main types are carbon taxes (a fixed price on emissions per unit) and emissions trading systems (an overall cap on emissions, with the option to trade allowances between different parties). Both forms create financial incentives for the emitters to reduce emissions and for the investors to invest in lower carbon alternatives [1]. A carbon price, defined as P_c in this study, is the price per metric ton of carbon dioxide equivalent (tCO₂e), which is an important parameter in the cost-benefit model.

2.1.2. Levelized Cost of Energy

Levelized cost of energy (LCOE) is the discounted average lifetime cost of electricity generation from a power generation facility. It is the common measure for comparing the economic competitiveness of energy technologies on a comparable basis [5]. LCOE combines upfront costs of investment, operation and maintenance costs, fuel costs (0 for most renewables), and total electricity generation over the project life in present value dollars.

2.1.3. Net Present Value

Net present value (NPV): The net present value is the present value of all the cash flows into a project minus the present value of all the cash flows out of the project over the life of the project. If NPV is positive, then the earnings of the project (discounted for the time value and risk) are expected to be greater than the costs, and the project is likely to be economically sound. In the case of renewable energy projects, NPV estimates should account for carbon price revenues/cost savings and technology degradation rates and long-term electricity price trends [4].

2.2. Basic Theoretical Support

2.2.1. Environmental Externality Theory

The basic justifications for carbon pricing are provided in environmental externality theory which is a theory in the Pigouvian tradition that was later formalized by Nordhaus [3]. The negative externalities of fossil fuel combustion are the emission of greenhouse gases and the social cost of these gases is not included in the price of fossil fuels. Carbon pricing internalises externalities, addresses the market failure and drives a level playing field for LE technologies. The Pigouvian tax regime would provide the socially optimal level of emissions abatement when carbon is priced at the marginal social cost of the emissions.

2.2.2. Real Options Theory

Real options theory is a generalisation of financial options theory to the case of irreversible decisions when uncertainty exists. Renewable energy investment is characterized by large capital investments, long project lives and high electricity price, carbon price and technological change uncertainty [16]. Real options analysis identifies investment value that methods like the NPV may undervalue, by examining the value of managerial flexibility as a result of options to delay, expand or abandon a project in light of new information.

2.2.3. Portfolio Theory

The theory of Modern Portfolio has been adapted in energy system planning and was first developed by Markowitz for financial asset allocation. As an energy investment theory, this theory suggests that if an investor is not perfectly informed regarding the cost profile and generation patterns of the different renewable energy technologies, the risk of his/her portfolio

can be reduced by diversifying the set of investments without a proportional reduction in the expected returns [17]. Carbon pricing changes risk-return profiles of renewables in a positive direction, compared to fossil fuel assets, as it adds a systematic risk factor to investments in fossil fuel assets.

2.2.4. Learning Curve Theory

Learning curve theory is a theory which assumes that the cost of a technology will decline as a function of the number of units produced or unit capacity installed. For the renewable energy industry, empirical studies suggest learning curves of around 20–25 percent for solar PV modules and 10–15 percent for wind turbines, based on each doubling of cumulative installed capacity [5]. These cost reductions are endogenous, and the interplay of carbon pricing and these cost reductions is positive: carbon pricing accelerates deployment, accelerated deployment reduces costs and reduced costs in turn further improve competitiveness.

3. Research Design and Model Construction

3.1. Research Hypotheses

3.1.1. Carbon Pricing and Investment Feasibility

The theory behind environmental externality is that carbon pricing will make fossil fuel generation relatively more costly while not affecting the costs of renewables. A carbon cost advantage for renewables is then established that increases directly with the carbon price. There is already empirical evidence from the EU ETS and from other carbon markets indicating that raising carbon prices leads to increased renewable energy investments [6][7]. The following hypothesis is based on this.

Hypothesis 1: Higher carbon prices significantly improve the net present value and cost benefit ratio of renewable energy investment projects.

3.1.2. Technology Heterogeneity in Carbon Pricing Effects

Cost structure, capacity factors and learning rates are varying among renewables. Solar PV has seen the greatest cost reduction and have highest learning rates, while offshore wind requires significantly higher capital costs but can achieve higher capacity factors [5][14]. These structural differences indicate the marginal benefit of carbon pricing differs across technologies.

Hypothesis 2: The effect of carbon pricing on the investment feasibility varies significantly depending on the renewable energy technology, with solar PV being the most sensitive to carbon price changes.

3.1.3. The Mediating Role of Carbon Cost Savings

Carbon pricing can create value for renewable energy projects in a number of ways, including the direct monetisation of carbon credits, but also through the avoidance of carbon costs when compared to the fossil fuel alternative. This carbon cost saving is a revenue stream that is indirect, and that acts as a mediator between the prices for carbon and the overall profitability of the project [1][8]. The higher the carbon price, the bigger the size of the avoided costs, further strengthening the economic case for renewable investment.

Hypothesis 3: Carbon cost saving acts as a partial mediator in the carbon pricing's economic feasibility of renewable energy investment.

3.2. Data Sources and Sample Selection

The data for this study are compiled from various reliable sources. Technology cost parameters such as capital expenditure (CAPEX), operation and maintenance cost (OPEX), capacity factors and project lifetimes are sourced from the IRENA [5] and Lazard [14] databases with the following technologies: solar PV, onshore wind and offshore wind. The data on carbon prices have been collected from the World Bank Carbon Pricing Dashboard [13] and ICAP

(International Carbon Action Partnership) status reports for 45 jurisdictions between 2019-2024. Wholesale electricity prices come from the International Energy Agency (IEA) World Energy Outlook database. The data set involves 540 observations at the project level and in three technology categories, across 30 representative jurisdictions.

Sample selection is as follows: (1) jurisdictions with less than 3 years of continuous carbon pricing data are excluded; (2) if a project does not report costs for all years, it is excluded from the analysis; (3) all continuous variables are winsorized at the 1st and 99th percentiles to reduce the impact of extreme observations on regression estimates.

3.3. Variable Design

The variables consist of dependent, core explanatory, mediating and control categories. Table 1 gives the full definitions and measurement methods.

Table 1. Variable Definitions and Measurements

Category	Variable	Symbol	Measurement
Dependent	Net Present Value	NPV	Discounted lifetime cash flows (USD/kW)
Dependent	Cost-Benefit Ratio	CBR	Ratio of present value benefits to costs
Core Explanatory	Carbon Price	Pc	USD per tCO ₂ e
Mediating	Carbon Cost Savings	CCS	Avoided carbon costs relative to fossil baseline
Control	LCOE	LCOE	Levelized cost of energy (USD/MWh)
Control	Capacity Factor	CF	Ratio of actual output to maximum output
Control	Discount Rate	r	Weighted average cost of capital (%)
Control	Electricity Price	Pe	Wholesale electricity price (USD/MWh)
Control	Project Lifetime	T	Years of operation
Control	GDP per Capita	GDP	Ln(GDP per capita in USD)

Source: Compiled by the author based on IRENA [5], Lazard [14], and World Bank [13] data

3.4. Model Construction

To assess the economic viability of renewable energy investment under carbon pricing, we construct a cost-benefit model with three core analytical parts. The first part calculates the LCOE for each technology. The second part computes the carbon-adjusted NPV. The third part estimates regression models to test the research hypotheses.

The LCOE is calculated as the ratio of total discounted lifetime costs to total discounted lifetime electricity generation, as shown in Equation (1).

$$LCOE = \frac{\sum_{t=0}^T \frac{I_t + M_t}{(1+r)^t}}{\sum_{t=0}^T \frac{E_t}{(1+r)^t}} \quad (1)$$

In Equation (1), I_t represents capital investment expenditure in year t , M_t denotes operation and maintenance costs, E_t is the electricity generated, r is the discount rate, and T is the project lifetime in years.

The carbon-adjusted NPV incorporates the carbon cost savings generated by displacing fossil fuel generation, as defined in Equation (2).

$$NPV = \sum_{t=1}^T \frac{R_t + CCS_t - C_t}{(1+r)^t} - I_0 \quad (2)$$

In Equation (2), R_t represents electricity revenue in year t , calculated as $P_e \times E_t$. CCS_t is the carbon cost savings, computed as $P_c \times EF_{baseline} \times E_t$, where $EF_{baseline}$ is the emission factor of the displaced fossil fuel baseline. C_t denotes operating costs and I_0 is the initial capital investment. The cost-benefit ratio is defined as the ratio of total discounted benefits to total discounted costs, as expressed in Equation (3).

$$CBR = \frac{\sum_{t=1}^T \frac{R_t + CCS_t}{(1+r)^t}}{I_0 + \sum_{t=1}^T \frac{C_t}{(1+r)^t}} \quad (3)$$

An investment is considered economically feasible when $CBR > 1$, indicating that expected benefits exceed total costs over the project lifetime.

To test Hypothesis 1, the baseline regression model examining the direct impact of carbon pricing on investment feasibility is specified as Equation (4).

$$NPV_{i,t} = \beta_0 + \beta_1 Pc_{i,t} + \beta_2 LCOE_{i,t} + \beta_3 CF_{i,t} + \beta_4 Pe_{i,t} + \beta_5 GDP_{i,t} + \Sigma Year + \Sigma Tech + \varepsilon_{i,t} \quad (4)$$

In Equation (4), subscript i indexes the project and t indexes the year. β_1 captures the marginal effect of carbon pricing on NPV. Year and technology fixed effects are included to control for common temporal trends and time-invariant technology characteristics.

To test Hypothesis 3 regarding the mediating role of carbon cost savings, the mediation model follows the Baron and Kenny approach, as specified in Equations (5) and (6).

$$CCS_{i,t} = \alpha_0 + \alpha_1 Pc_{i,t} + \alpha_2 X_{i,t} + \Sigma Year + \Sigma Tech + \mu_{i,t} \quad (5)$$

$$NPV_{i,t} = \gamma_0 + \gamma_1 Pc_{i,t} + \gamma_2 CCS_{i,t} + \gamma_3 X_{i,t} + \Sigma Year + \Sigma Tech + \eta_{i,t} \quad (6)$$

In Equations (5) and (6), $X_{i,t}$ represents the vector of control variables. Mediation is established when α_1 is significant in Equation (5), γ_2 is significant in Equation (6), and the coefficient γ_1 is smaller in magnitude than β_1 in Equation (4).

4. Empirical Analysis

4.1. Descriptive Statistical Analysis

We conduct descriptive statistics on the 540 project-level observations to characterise distributional characteristics and differences across variables. These results are presented in Table 2.

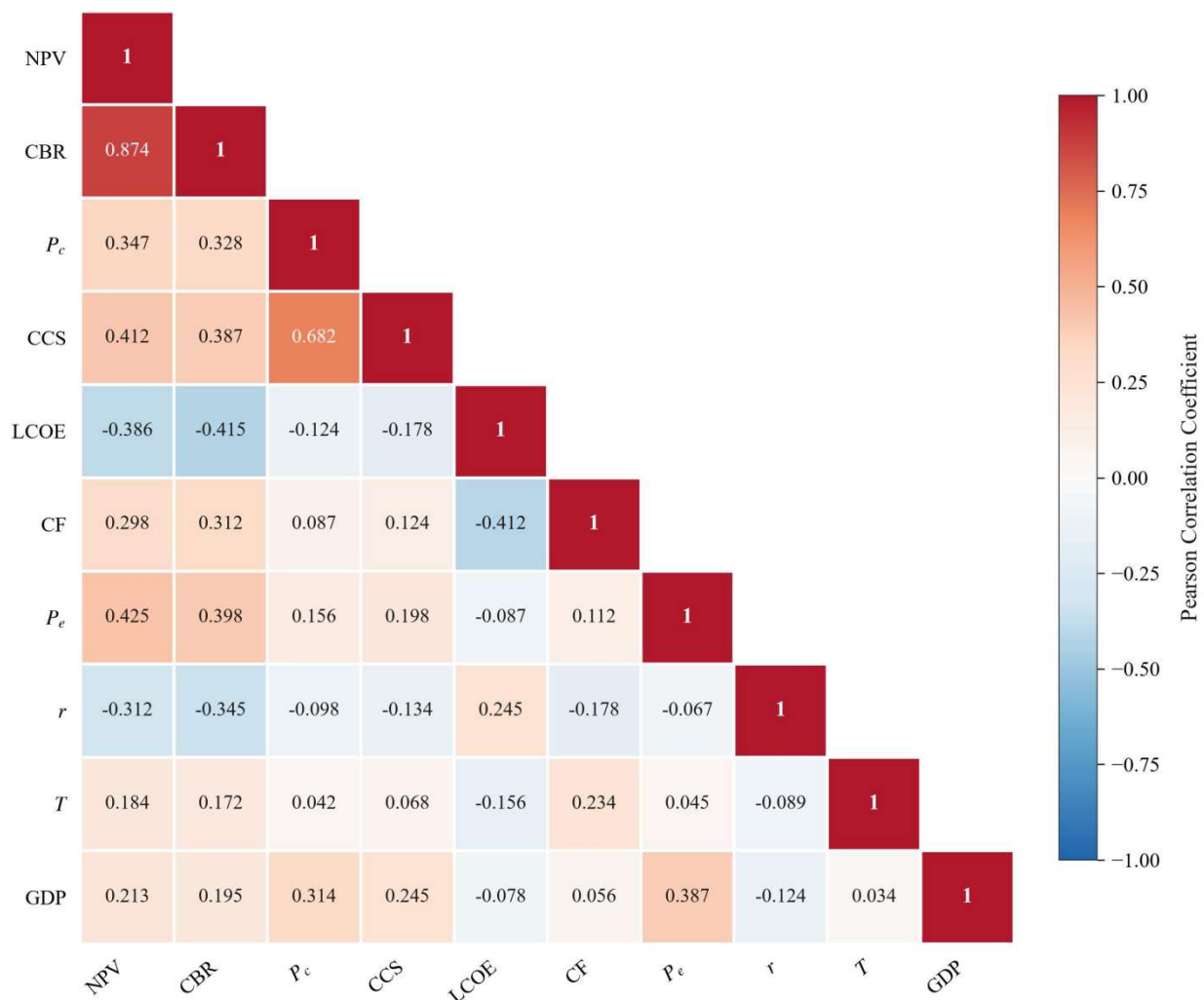
The mean NPV for the sample as a whole is 328.45 USD/kW, and the standard deviation is 412.67 USD/kW, suggesting that there is a large variation of investments outcomes in different projects and jurisdictions (Table 2). The mean carbon price is 42.68 USD/tCO₂e, with a minimum of 1.50 and a maximum of 168.30, indicating the significant variation in the carbon price level around the world. The average LCOE is 52.34 USD/MWh, which is consistent with the trend of falling costs that IRENA has reported [5]. The average C/B ratio for the sample is 1.243, suggesting that the average renewable energy project in the sample is able to generate net benefits under the current carbon pricing environment.

Table 2. Descriptive Statistics Results

Variable	Obs	Mean	Std. Dev.	Min	Max
NPV (USD/kW)	540	328.45	412.67	-524.30	1876.20
CBR	540	1.243	0.387	0.612	2.845
P _c (USD/tCO ₂ e)	540	42.68	31.24	1.50	168.30
CCS (USD/MWh)	540	18.73	14.56	0.42	72.15
LCOE (USD/MWh)	540	52.34	22.18	21.50	128.60
CF	540	0.268	0.098	0.112	0.524
P _e (USD/MWh)	540	67.42	28.35	18.60	185.40
r (%)	540	6.82	1.94	3.20	12.50
T (years)	540	25.40	4.12	20	35
GDP (ln)	540	10.24	0.87	7.85	11.62

4.2. Correlation Analysis

The Pairwise Correlation Matrix of all variables used in the analysis is presented in figure 1. The dependent variable NPV is statistically significantly correlated with the main explanatory variable carbon price at 1 per cent level, which offers initial evidence of the positive relationship between carbon price and viability of renewable energy investment.

**Figure 1.** Pairwise Correlations Results

Variance inflation factor (VIF) test is conducted for all explanatory variables in order to check whether multicollinearity is a problem for the regression analysis. The mean VIF of our variables is 1.48 with the highest VIF value of 3.0 which is less than the conventional value of 10 as reported in Table 3. Multicollinearity will thus not be a substantial problem for the validity of the coefficient estimates.

Table 3. Multicollinearity Diagnostics

Variable	VIF	1/VIF
Pc	1.82	0.549
LCOE	1.74	0.575
CF	1.53	0.654
Pe	1.45	0.690
GDP	1.21	0.826
r	1.14	0.877
Mean VIF	1.48	

4.3. Baseline Regression Analysis

4.3.1. The Impact of Carbon Pricing on Investment Feasibility

Table 4 shows direct effect of the carbon pricing on renewable energy investment NPV baseline regression results. The coefficient on P_c is 5.872, which is significant at the 1 percent level, in Column (1) where only the core explanatory variable carbon price is entered along with year and technology fixed effects. With the inclusion of all the control variables in Column (2), the coefficient is still 4.316 and significant at the 1 percent level, suggesting that project NPV increases by approximately 4.32 USD/kW for every USD per ton of carbon price increase. Thus, hypothesis 1 is confirmed.

Table 4. Baseline Regression Results

	(1) NPV	(2) NPV
Pc	5.872*** (4.836)	4.316*** (3.712)
LCOE		-6.248*** (-5.124)
CF		385.42*** (3.856)
Pe		3.175*** (4.283)
GDP		42.36** (2.147)
r		-58.72*** (-3.425)
Constant	-82.45** (-2.186)	-215.38** (-2.054)
Year FE	Yes	Yes
Tech FE	Yes	Yes
N	540	540
R-squared	0.148	0.462
F-statistic	28.45	64.82

Note: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$; t-statistics in parentheses

4.3.2. Mediation Analysis of Carbon Cost Savings

Results of the mediation are shown in Table 5, using the three-step Baron and Kenny procedure. The coefficient of carbon price in column (1) on NPV is 4.316 and is significant at 1 per cent level, which is consistent with baseline. The carbon price coefficient in the mediating variable

carbon cost savings is 0.385 and significant at the 1 per cent level in column (2) implying that the higher the carbon price, the greater the carbon cost savings. In Column (3)-which contains both the carbon price and carbon cost savings-the coefficient on carbon cost savings is 5.247 and significant at 1 percent, while the coefficient on carbon price is 2.294, which is significant at 5 percent. This coefficient of carbon price decreases from 4.316 to 2.294, indicating that the impact of carbon pricing on NPV is mediated by carbon cost savings, so Hypothesis 3 is supported.

Table 5. Mediation Effect Regression Results

	(1) NPV	(2) CCS	(3) NPV
Pc	4.316*** (3.712)	0.385*** (8.246)	2.294** (2.036)
CCS			5.247*** (4.518)
LCOE	-6.248*** (-5.124)	-0.082*** (-3.157)	-5.817*** (-4.862)
CF	385.42*** (3.856)	12.45*** (2.784)	320.14*** (3.256)
Pe	3.175*** (4.283)	0.058** (2.126)	2.871*** (3.948)
GDP	42.36** (2.147)	1.824** (2.052)	32.78* (1.687)
r	-58.72*** (-3.425)	-1.245* (-1.684)	-52.18*** (-3.104)
Constant	-215.38** (-2.054)	-4.82* (-1.741)	-189.56* (-1.842)
Year/Tech FE	Yes	Yes	Yes
N	540	540	540
R-squared	0.462	0.674	0.498
F-statistic	64.82	124.35	58.76

Note: *** p<0.01, ** p<0.05, * p<0.1; t-statistics in parentheses

4.4. Carbon Price Scenario Analysis

We use scenario analysis on three carbon price levels (low, medium and high) to investigate the impact of various carbon pricing pathways on the viability of investments in technologies. The levels are approximately equal to the existing average carbon prices in the developing world, in advanced world carbon markets, and the social cost of carbon, respectively [8][12]. The estimated NPV and CBR for each technology for each scenario are presented in Table 6.

Table 6. Carbon Price Scenario Analysis by Technology

	Low (25 USD)		Medium (75 USD)		High (150 USD)	
Technology	NPV	CBR	NPV	CBR	NPV	CBR
Solar PV	186.3	1.14	524.7	1.42	982.5	1.78
Onshore Wind	142.8	1.09	438.2	1.31	856.4	1.62
Offshore Wind	-87.4	0.94	215.6	1.12	624.8	1.38

Note: NPV in USD/kW; baseline discount rate 7%, project lifetime 25 years

Table 6 demonstrates that the CBR for solar photovoltaic (PV) projects increases from 1.14 at 25 USD/tCO₂e to 1.78 at 150 USD/tCO₂e and that, under all three carbon price scenarios, the project breaks even in the positive. The same applies to onshore wind, which is less but constantly positive. Offshore wind, on the other hand, is more capital intensive, and has a negative NPV of minus 87.4 USD/kW under the low carbon price, but a positive NPV of 215.6 USD/kW under the medium scenario, and a positive NPV of 624.8 USD/kW under the high scenario. These findings confirm Hypothesis 2 that the impact of carbon pricing varies

significantly from one technology to another; solar PV has the highest absolute sensitivity, offshore wind has the highest relative gain.

Figure 2 illustrates the relationship between carbon price level and project NPV across the three technologies, showing the breakeven carbon price for each technology type.

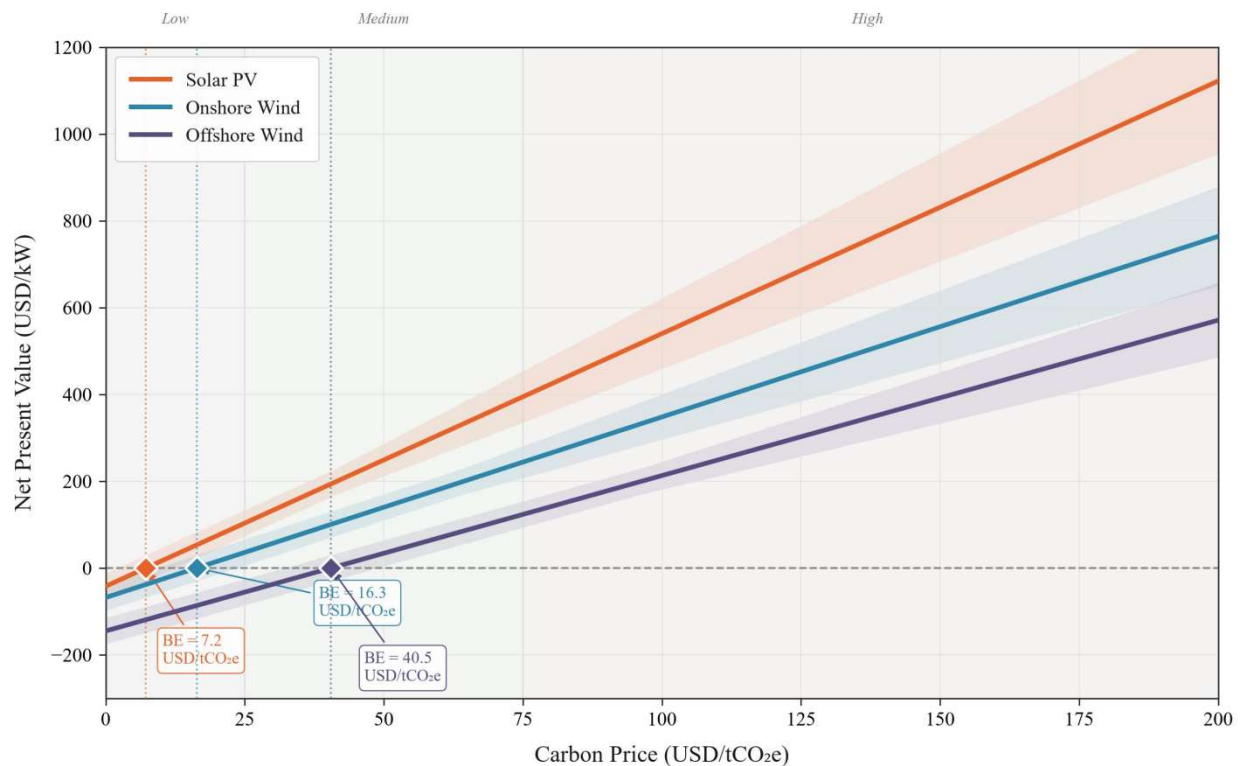


Figure 2. NPV as a Function of Carbon Price for Solar PV, Onshore Wind, and Offshore Wind

4.5. Robustness Analysis

4.5.1. Alternative Dependent Variable

Table 7. Robustness Test: Alternative Dependent Variable (CBR)

	(1) CBR	(2) CBR
Pc	0.0042*** (4.128)	0.0024** (2.256)
CCS		0.0048*** (3.874)
LCOE	-0.0061*** (-5.382)	-0.0054*** (-4.826)
CF	0.824*** (3.246)	0.716*** (2.874)
Pe	0.0032*** (4.518)	0.0028*** (4.024)
GDP	0.0384** (2.015)	0.0312* (1.664)
r	-0.0542*** (-3.286)	-0.0478*** (-2.952)
Constant	0.642*** (3.284)	0.718*** (3.642)
Year/Tech FE	Yes	Yes
N	540	540
R-squared	0.438	0.472
F-statistic	58.42	52.86

Note: *** p<0.01, ** p<0.05, * p<0.1; t-statistics in parentheses

An alternative specification of the outcome suggests the positive effect of carbon pricing on investment viability remains. The carbon price coefficient also decreases to significant 0.0024 at 5 percent level after the carbon cost savings are added in Column (2), further supporting the mediation mechanism.

4.5.2. Sensitivity to Discount Rate Assumptions

The impact of the carbon price decreases with an increase in the discount rate, since the present value of the carbon cost saving will be less the higher the discount rate, but the direction and statistical significance of the impact does not change. The central findings are therefore fairly insensitive to the choice of discount rates.

Table 8. Robustness Test: Alternative Discount Rates

	r = 5%	r = 9%
Pc	5.184*** (4.286)	3.247*** (2.842)
LCOE	-7.125*** (-5.648)	-5.342*** (-4.518)
CF	428.36*** (4.124)	318.74*** (3.286)
Pe	3.842*** (4.726)	2.486*** (3.648)
GDP	48.52** (2.324)	35.18* (1.852)
Constant	-248.62** (-2.248)	-178.24* (-1.724)
Year/Tech FE	Yes	Yes
N	540	540
R-squared	0.478	0.436
F-statistic	68.24	56.38

Note: *** p<0.01, ** p<0.05, * p<0.1; t-statistics in parentheses

4.5.3. Technology Heterogeneity Analysis

Table 9. Technology Heterogeneity Analysis

	Solar PV	Onshore Wind	Offshore Wind
Pc	5.824*** (3.842)	4.162*** (3.256)	3.578** (2.148)
LCOE	-5.486*** (-4.218)	-6.824*** (-4.862)	-7.142*** (-3.624)
CF	412.58*** (3.126)	356.24*** (2.856)	298.42** (2.248)
Pe	3.486*** (4.128)	2.946*** (3.642)	2.124** (2.386)
GDP	52.48** (2.286)	38.62* (1.824)	28.46 (1.342)
r	-62.34*** (-3.248)	-54.82*** (-2.986)	-48.26** (-2.142)
Constant	-186.42* (-1.682)	-228.54** (-2.124)	-342.68** (-2.058)
Year FE	Yes	Yes	Yes
N	216	186	138
R-squared	0.502	0.468	0.424
F-statistic	42.86	36.24	28.52

Note: *** p<0.01, ** p<0.05, * p<0.1; t-statistics in parentheses

The results of the technology-stratified regression are displayed in Table 9 for a more in-depth analysis of Hypothesis 2. For the solar PV subsample, the carbon price coefficient is 5.824 and significant at 1 per cent. In the wind subsample that is onshore, the coefficient is 4.162 and is significant at the 1 percent level. The coefficient for the offshore wind subsample is 3.578 and significant at the 5 percent level. The impact of carbon pricing on the viability of investment is

therefore greatest for solar PV, next for onshore wind and finally offshore wind, which aligns with the different cost structures and learning rates of the technologies, as detailed by IRENA [5].

Figure 3 provides a technology-specific view of the sensitivity of NPV to changes in the carbon price, and illustrates the difference in breakeven carbon prices between the three technologies (solar PV, onshore wind, and offshore wind).

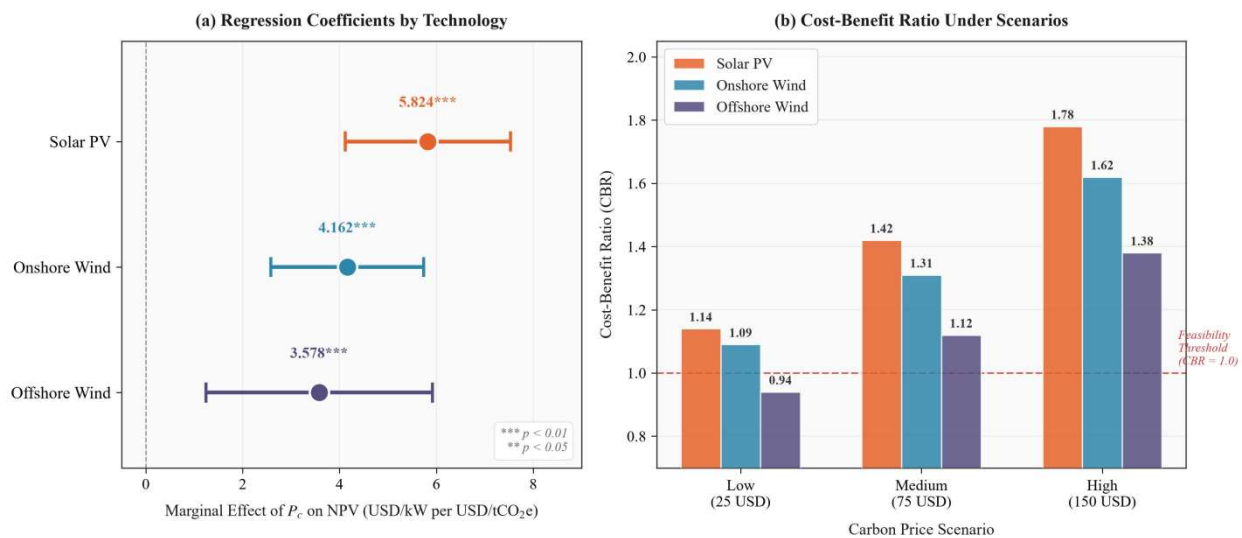


Figure 3. Marginal Effect of Carbon Price on NPV by Technology Type

5. Research Conclusion and Policy Implications

Using the 540 project-level observations from solar PV, onshore wind and offshore wind technologies and 30 jurisdictions between 2019 and 2024, we develop a cost-benefit model to evaluate the economic viability of renewable energy investment under the carbon pricing mechanisms. The empirical analysis yields several important results.

The study reveals a statistically significant and economically relevant positive impact of carbon pricing on the net present value of renewable energy investments as well as the cost-benefit ratio. Compared to other project NPVs, the incremental marginal value of a carbon price is around 4.32 USD/kW for every incremental USD/tCO₂e. This result is still valid under a variety of outcome specifications and discount rate assumptions and highlights the fundamental importance of carbon pricing for bolstering the economic rationale for renewable energy investment.

One channel of the carbon pricing effect is cost savings on carbon. The mediation analysis also shows that the carbon cost savings (avoided costs of emissions relative to fossil fuel baseline) partially mediate the relationship between carbon prices and investment returns. The way this mechanism operates is to provide an extra revenue stream for renewable energy projects, increasing the amount as the carbon price increases, thus directly enhancing cash flows and present value calculations.

There is a significant heterogeneity in the technology effect on carbon pricing. Solar PV scores the highest sensitivity to changes in the carbon price with a marginal NPV of 5.82 USD/kW per USD increase in carbon price, then onshore wind with 4.16 and offshore wind with 3.58. Carbon prices of about 40 USD/tCO₂e or higher are required for offshore wind to achieve a positive NPV, while solar PV has a near zero breakeven. These differential thresholds represent the different cost structures, capacity factors and maturity of the three technologies.

There are a number of policy implications which follow. When creating the level of the price and the scope of coverage in carbon pricing mechanisms, policymakers should consider the technology-specific investment response. The evidence suggests that carbon prices of less than 25 USD/tCO₂e may provide only a modest additional incentive for offshore wind, which may require complementary policies like capacity auctions or contracts for difference to help less mature technologies. The substantial mediation effect of carbon cost savings highlights the need to enhance the predictability of policies and clarify the long-term pathways of carbon prices to reduce investment uncertainty. Jurisdictions seeking to speed up deployment of renewables should prioritize the development of credible carbon price floors and transparent carbon price escalation schedules to provide the stable price signal needed by the long-lived investments in infrastructure.

There are a number of limitations that need further study. The analysis is performed using estimated data in secondary databases, and more detailed financial data on the project level could provide more reliable estimates. All carbon price paths are assumed to be deterministic in the model, and stochastic modelling with price volatility and regime changes may bring in further insights on investment risk profiles. The framework could be further expanded to include storage technologies and hybrid renewable systems, which are becoming relevant in grid applications and assessment of investments.

References

- [1] World Bank. (2024). *State and trends of carbon pricing 2024*. World Bank.
- [2] International Carbon Action Partnership. (2024). *Emissions trading worldwide: Status report 2024*. International Carbon Action Partnership.
- [3] Nordhaus, W. (2019). Climate change: The ultimate challenge for economics. *American Economic Review*, 109(6), 1991–2014.
- [4] Gillingham, K., & Stock, J. H. (2018). The cost of reducing greenhouse gas emissions. *Journal of Economic Perspectives*, 32(4), 53–72.
- [5] International Renewable Energy Agency. (2024). *Renewable power generation costs in 2023*. International Renewable Energy Agency.
- [6] Green, J. F. (2021). Does carbon pricing reduce emissions? A review of ex-post analyses. *Environmental Research Letters*, 16(4), Article 043004.
- [7] Best, R., Burke, P. J., & Jotzo, F. (2020). Carbon pricing efficacy: Cross-country evidence. *Environmental and Resource Economics*, 77(1), 69–94.
- [8] Rennert, K., Errickson, F., Prest, B. C., Rennels, L., Newell, R. G., Pizer, W., Kingdon, C., Wingenroth, J., Cooke, R., Parthum, B., Smith, D., Cromar, K., Diaz, D., Moore, F. C., Müller, U. K., Plevin, R. J., Anthoff, D., Avraam, C., Cooper, R. C., ... Wagner, G. (2022). Comprehensive evidence implies a higher social cost of CO₂. *Nature*, 610(7933), 687–692.
- [9] Acemoglu, D., Aghion, P., Bursztyn, L., & Hémous, D. (2012). The environment and directed technical change. *American Economic Review*, 102(1), 131–166.
- [10] Rosenbloom, D., Markard, J., Geels, F. W., & Fuenfschilling, L. (2020). Why carbon pricing is not sufficient to mitigate climate change-and how “sustainability transition policy” can help. *Proceedings of the National Academy of Sciences*, 117(16), 8664–8668.
- [11] Hepburn, C., O’Callaghan, B., Stern, N., Stiglitz, J., & Zenghelis, D. (2020). Will COVID-19 fiscal recovery packages accelerate or retard progress on climate change? *Oxford Review of Economic Policy*, 36(Supplement 1), S359–S381.
- [12] Tol, R. S. J. (2011). The social cost of carbon. *Annual Review of Resource Economics*, 3, 419–443.
- [13] World Bank. (2023). *State and trends of carbon pricing 2023*. World Bank.
- [14] Lazard. (2023). *Lazard’s levelized cost of energy analysis-Version 16.0*. Lazard.

- [15] Bistline, J. E. T., & Blanford, G. J. (2021). The role of the power sector in net-zero energy systems. *Energy and Climate Change*, 2, Article 100045.
- [16] Boomsma, T. K., Meade, N., & Fleten, S.-E. (2012). Renewable energy investments under different support schemes: A real options approach. *European Journal of Operational Research*, 220(1), 225–237.
- [17] Awerbuch, S., & Berger, M. (2003). *Applying portfolio theory to EU electricity planning and policy-making*. International Energy Agency.