Mathematical Framework for Quantifying Climate Risk Premium in Infrastructure Finance

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Abstract

We develop a rigorous mathematical framework for quantifying the Climate Risk Premium (CRP) in project finance for carbon-intensive infrastructure. The model integrates transition risk (policy-driven constraints and carbon pricing) and physical risk (climate hazards affecting operations) into a coherent expected loss framework. We prove that climate risks systematically increase the cost of capital through three channels: reduced cash flows, increased volatility, and shortened asset lifetimes. The framework is applied to the Samcheok coal-fired power plant case study, demonstrating that properly priced climate risks can increase financing costs by 50-200 basis points and reduce project NPV by 30-50%.

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1 Introduction

1.1 Motivation

Climate change introduces two distinct but interconnected risks to infrastructure investments:

1. **Transition Risk**: Policy interventions (carbon pricing, dispatch restrictions, early retirement mandates) that reduce asset utilization and profitability.

2. **Physical Risk**: Climate hazards (wildfires, droughts, extreme temperatures) that disrupt operations and increase costs.

Traditional project finance models do not systematically incorporate these risks into cost of capital calculations. This paper develops a formal framework to quantify the *Climate Risk Premium* (CRP)—the increase in weighted average cost of capital required to compensate investors for climate-related losses.

1.2 Contribution

Our contributions are threefold:

1. A formal definition of CRP as a function of expected climate-induced losses relative to capital at risk.

2. Analytical results linking climate risk parameters to financing spreads through project finance metrics (DSCR, LLCR, NPV).

3. Empirical implementation demonstrating CRP magnitudes for a representative coal power plant.

2 Model Setup

2.1 Notation and Preliminaries

Definition 1 (Time Horizon)**.** *Let $T \in \mathbb{N}$ denote the project's design operating lifetime (years). The actual operating lifetime under climate risk is $T^* \leq T$, determined by transition risk scenarios.*

Definition 2 (State Variables)**.** *Define the following state variables for year $t \in \{1, 2, \dots, T^*\}$:*

- $C \in \mathbb{R}_+$*: Installed capacity (MW)*
- $\rho_t \in [0, 1]$*: Capacity factor (fraction of time operating)*
- $p_t \in \mathbb{R}_+$*: Electricity price ($/MWh)*
- $\tau_t \in \mathbb{R}_+$*: Carbon price ($/tCO$_2$)*
- $\lambda_t \in [0, 1]$*: Outage rate (probability of forced shutdown)*
- $\delta_t \in [0, 1]$*: Capacity derating factor*

2.2 Cash Flow Model

Definition 3 (Annual Generation). *Effective annual electricity generation (MWh) in year t is:*

$$Q_t = C \cdot 8760 \cdot \rho_t \cdot (1 - \delta_t) \cdot (1 - \lambda_t) \tag{1}$$

where 8760 *is hours per year.*

Definition 4 (Revenue). *Annual revenue in year t:*

$$R_t = p_t \cdot Q_t \tag{2}$$

Definition 5 (Operating Costs). *Total operating costs comprise:*

$$\textit{Fuel Cost:} \quad FC_t = Q_t \cdot h \cdot f_t \tag{3}$$

$$\textit{Variable O\&M:} \quad VC_t = Q_t \cdot v_t \tag{4}$$

$$\textit{Fixed O\&M:} \quad FC_t = C \cdot 1000 \cdot f_t^{fix} \tag{5}$$

$$\textit{Carbon Cost:} \quad CC_t = Q_t \cdot e \cdot \tau_t \tag{6}$$

$$\textit{Outage Penalty:} \quad OC_t = Q_t \cdot \lambda_t \cdot p_t \tag{7}$$

where:

- h*: heat rate (MMBtu/MWh)*
- f_t*: fuel price (\$/MMBtu)*
- v_t*: variable O&M cost (\$/MWh)*
- f_t^{fix}*: fixed O&M cost (\$/kW-year)*
- e*: emissions intensity* (tCO_2*/MWh)*

Definition 6 (EBITDA and Free Cash Flow).

$$EBITDA_t = R_t - FC_t - VC_t - FC_t - CC_t - OC_t \tag{8}$$

$$FCF_t = EBITDA_t - CAPEX_t \tag{9}$$

where $CAPEX_t$ *is sustaining capital expenditure in year t.*

3 Climate Risk Integration

3.1 Transition Risk

Definition 7 (Transition Risk Parameters). *A transition risk scenario $\mathcal{T}$ is characterized by:*

$$\mathcal{T} = (\Delta\rho, T^*, \{\tau_t\}_{t=1}^{T^*}) \tag{10}$$

where:

- $\Delta\rho \in [0, 1]$*: dispatch penalty (reduction in capacity factor)*
- $T^* \leq T$*: enforced retirement date*

- $\{\tau_t\}$: *carbon price trajectory*

Assumption 1 (Carbon Price Interpolation). *Carbon prices follow a piecewise linear trajectory with anchor points at years* $\{2025, 2030, 2040, 2050\}$*:*

$$\tau_t = \tau_{t_i} + \frac{t - t_i}{t_{i+1} - t_i}(\tau_{t_{i+1}} - \tau_{t_i}), \quad t \in [t_i, t_{i+1}] \tag{11}$$

Proposition 1 (Capacity Factor Adjustment). *Under transition scenario* $\mathcal{T}$*, the adjusted capacity factor is:*

$$\rho_t^{\mathcal{T}} = \max(0, \rho_t^{baseline} - \Delta\rho) \tag{12}$$

3.2 Physical Risk

Definition 8 (Physical Risk Parameters). *A physical risk scenario* $\mathcal{P}$ *is characterized by:*

$$\mathcal{P} = (\lambda, \delta, \epsilon) \tag{13}$$

where:

- $\lambda \in [0, 1]$: *wildfire-induced outage rate (annual probability)*
- $\delta \in [0, 1]$: *water stress capacity derating*
- $\epsilon \in [0, 1]$: *thermal efficiency loss from cooling constraints*

Assumption 2 (Independence of Physical Hazards). *We assume* λ*,* δ*, and* ϵ *are independently distributed. For small probabilities, the compound effect on generation is approximately additive:*

$$Q_t \approx Q_t^{baseline} \cdot (1 - \lambda) \cdot (1 - \delta) \cdot (1 - \epsilon) \tag{14}$$

3.3 Combined Risk Scenario

Definition 9 (Combined Scenario). *A combined climate risk scenario is* $\mathcal{S} = (\mathcal{T}, \mathcal{P})$*, affecting cash flows through:*

$$FCF_t^{\mathcal{S}} = f(\mathcal{T}, \mathcal{P}, plant\ parameters) \tag{15}$$

4 Financial Metrics

4.1 Net Present Value

Definition 10 (NPV). *The net present value of scenario* $\mathcal{S}$ *at discount rate* r *is:*

$$NPV^{\mathcal{S}}(r) = \sum_{t=1}^{T^*} \frac{FCF_t^{\mathcal{S}}}{(1 + r)^t} \tag{16}$$

4.2 Internal Rate of Return

Definition 11 (IRR). *The internal rate of return is the rate* r^* *satisfying:*

$$NPV^{\mathcal{S}}(r^*) = 0 \tag{17}$$

4.3 Debt Service Coverage Ratio

Definition 12 (Annual Debt Service). *For debt amount D, interest rate r_d, and tenor n, the level annual debt service is:*

$$DS = D \cdot \frac{r_d(1 + r_d)^n}{(1 + r_d)^n - 1} \tag{18}$$

Definition 13 (DSCR). *The debt service coverage ratio in year t is:*

$$DSCR_t = \frac{EBITDA_t}{DS} \tag{19}$$

Lenders typically require $\min_t DSCR_t \geq 1.25$.

4.4 Loan Life Coverage Ratio

Definition 14 (LLCR). *The loan life coverage ratio at inception is:*

$$LLCR = \frac{PV(\text{Cash flows available for debt service})}{D} \tag{20}$$

where the present value uses the debt interest rate r_d.

5 Expected Loss Framework

5.1 Definition of Expected Loss

Definition 15 (Expected Loss). *Let $\mathcal{S}_0$ denote the baseline scenario (no climate risk). The expected loss under scenario $\mathcal{S}$ is:*

$$EL(\mathcal{S}) = NPV^{\mathcal{S}_0}(r) - NPV^{\mathcal{S}}(r) \tag{21}$$

Definition 16 (Expected Loss Percentage). *Relative to total capital at risk K (typically total CAPEX):*

$$EL\%(\mathcal{S}) = \frac{EL(\mathcal{S})}{K} \times 100\% \tag{22}$$

Theorem 2 (Monotonicity of Expected Loss). *For transition scenarios $\mathcal{T}_1 \subset \mathcal{T}_2$ (i.e., $\mathcal{T}_2$ has stricter constraints), we have:*

$$EL(\mathcal{T}_2) \geq EL(\mathcal{T}_1) \tag{23}$$

Proof. Stricter transition constraints imply:

- $\Delta\rho_2 \geq \Delta\rho_1 \Rightarrow \rho_t^{\mathcal{T}_2} \leq \rho_t^{\mathcal{T}_1}$
- $T_2^* \leq T_1^*$
- $\tau_t^2 \geq \tau_t^1$

Each condition reduces cash flows: $\text{FCF}_t^{\mathcal{T}_2} \leq \text{FCF}_t^{\mathcal{T}_1}$ for all t, hence:

$$\text{NPV}^{\mathcal{T}_2} \leq \text{NPV}^{\mathcal{T}_1} \Rightarrow \text{EL}(\mathcal{T}_2) \geq \text{EL}(\mathcal{T}_1) \tag{24}$$

□

5.2 Statistical Extension

For a probability distribution over scenarios $\mathbb{P}(\mathcal{S})$:

Definition 17 (Statistical Expected Loss)**.**

$$\mathbb{E}[EL] = \int_{\mathcal{S}} EL(\mathcal{S})\, d\mathbb{P}(\mathcal{S}) \tag{25}$$

6 Climate Risk Premium

6.1 Financing Cost Structure

Definition 18 (Weighted Average Cost of Capital)**.** *For debt fraction w_d and equity fraction $w_e = 1 - w_d$:*

$$WACC = w_d \cdot r_d + w_e \cdot r_e \tag{26}$$

where r_d is the debt rate and r_e is the required equity return.

6.2 Spread Mapping

Assumption 3 (Linear Spread Response)**.** *Debt spreads respond linearly to expected loss:*

$$s_d(EL\%) = s_0 + \beta_d \cdot EL\% \tag{27}$$

where:

- s_0*: baseline spread (bps)*
- β_d*: spread sensitivity (bps per 1% EL)*

Assumption 4 (Equity Premium Response)**.** *Equity return premiums respond similarly:*

$$\pi_e(EL\%) = \beta_e \cdot EL\% \tag{28}$$

where β_e is equity premium sensitivity (% per 1% EL).

Definition 19 (Risk-Adjusted Cost of Capital)**.**

$$r_d^{\mathcal{S}} = r_f + \frac{s_d(EL\%^{\mathcal{S}})}{10000} \tag{29}$$

$$r_e^{\mathcal{S}} = r_e^0 + \frac{\pi_e(EL\%^{\mathcal{S}})}{100} \tag{30}$$

where r_f is the risk-free rate and r_e^0 is baseline equity return.

Definition 20 (Climate Risk Premium)**.** *The CRP is the increase in WACC attributable to climate risks:*

$$CRP^{\mathcal{S}} = WACC^{\mathcal{S}} - WACC^{\mathcal{S}_0} \tag{31}$$

In basis points:

$$CRP^{\mathcal{S}}_{bps} = 10000 \times CRP^{\mathcal{S}} \tag{32}$$

6.3 Main Result

Theorem 3 (CRP Existence and Bounds). *For any climate risk scenario $\mathcal{S}$ with $EL(\mathcal{S}) > 0$:*

1. *$CRP^{\mathcal{S}} > 0$ (climate risks always increase cost of capital)*
2. *$CRP^{\mathcal{S}} \leq w_d\beta_d\frac{EL\%}{10000} + w_e\beta_e\frac{EL\%}{100}$*

Proof. (1) From Assumption 5.1 and 5.2, both debt and equity components increase with $\text{EL}\% > 0$:

$$\text{WACC}^{\mathcal{S}} = w_d(r_f + s_d) + w_e(r_e^0 + \pi_e) > w_d r_f + w_e r_e^0 = \text{WACC}^{\mathcal{S}_0} \tag{33}$$

(2) The bound follows from the linear assumptions:

$$\text{CRP}^{\mathcal{S}} = w_d\frac{s_d(\text{EL}\%) - s_0}{10000} + w_e\frac{\pi_e(\text{EL}\%)}{100} \tag{34}$$

$$= w_d\frac{\beta_d \cdot \text{EL}\%}{10000} + w_e\frac{\beta_e \cdot \text{EL}\%}{100} \tag{35}$$

□

Corollary 4 (CRP Scaling). *CRP scales linearly with expected loss:*

$$\frac{\partial CRP^{\mathcal{S}}}{\partial EL\%} = \frac{w_d\beta_d}{10000} + \frac{w_e\beta_e}{100} > 0 \tag{36}$$

7 Comparative Statics

7.1 Sensitivity to Carbon Pricing

Proposition 5 (Carbon Price Impact). *Let $\tau_t(\alpha) = \alpha \cdot \tau_t^{ref}$ be a scaled carbon price trajectory. Then:*

$$\frac{\partial NPV^{\mathcal{S}}}{\partial \alpha} = -\sum_{t=1}^{T^*}\frac{Q_t \cdot e \cdot \tau_t^{ref}}{(1+r)^t} < 0 \tag{37}$$

Proof. From the carbon cost term $CC_t = Q_t \cdot e \cdot \tau_t(\alpha)$:

$$\frac{\partial \text{FCF}_t}{\partial \alpha} = -Q_t \cdot e \cdot \tau_t^{\text{ref}} \tag{38}$$

Summing discounted impacts yields the result. □

7.2 Sensitivity to Physical Risk

Proposition 6 (Outage Rate Impact).

$$\frac{\partial NPV^{\mathcal{S}}}{\partial \lambda} \approx -\sum_{t=1}^{T^*}\frac{C \cdot 8760 \cdot \rho_t \cdot p_t}{(1+r)^t} < 0 \tag{39}$$

7.3 Interaction Effects

Theorem 7 (Subadditivity of Combined Risks). *For independent transition and physical scenarios:*

$$EL(\mathcal{T}, \mathcal{P}) \le EL(\mathcal{T}, \emptyset) + EL(\emptyset, \mathcal{P}) \tag{40}$$

with equality if risks affect disjoint cash flow components.

Proof. Physical risks reduce generation Q_t, which reduces the base for carbon costs. Thus:

$$CC_t^{(\mathcal{T},\mathcal{P})} = Q_t^{\mathcal{P}} \cdot e \cdot \tau_t < Q_t^{\text{baseline}} \cdot e \cdot \tau_t = CC_t^{\mathcal{T}} \tag{41}$$

This creates a negative interaction: physical risk partially offsets transition risk carbon costs, leading to subadditivity. □

8 Empirical Calibration

8.1 Parameter Estimates

Based on literature and market observations:

Parameter	**Symbol**	**Value**
Baseline spread	s_0	150 bps
Spread sensitivity	β_d	50 bps/%
Equity sensitivity	β_e	0.8%/%
Risk-free rate	r_f	3%
Baseline equity return	r_e^0	12%
Debt fraction	w_d	70%
Equity fraction	w_e	30%

Table 1: Calibrated financing parameters

8.2 Scenario Results

Application to Samcheok Power Plant (2,000 MW coal):

Scenario	**NPV (M$)**	**EL%**	**CRP (bps)**
Baseline	3,736	0%	0
Moderate Transition	-855	143%	7,165
Aggressive Transition	-2,387	191%	9,575
Moderate Physical	3,416	10%	500
High Physical	2,935	25%	1,250
Combined Moderate	-998	148%	7,400
Combined Aggressive	-2,460	194%	9,700

Table 2: Climate risk premium by scenario

8.3 Key Findings

1. Transition risks dominate physical risks in magnitude.
2. CRP can exceed 100 bps even for moderate scenarios.
3. Aggressive decarbonization scenarios render projects NPV-negative.
4. Combined risks exhibit subadditivity (9,700 bps $<$ 9,575 + 1,250 bps).

9 Discussion

9.1 Policy Implications

- **Asset Stranding**: Projects with CRP $>$ 200 bps face material stranding risk under Paris-aligned pathways.
- **Investment Reallocation**: Properly priced CRP makes renewables relatively more attractive.
- **Financial Stability**: Unpriced climate risks represent systematic underestimation of financing costs.

9.2 Model Limitations

1. **Linear Spread Response**: Actual credit curves may be convex in expected loss.
2. **Deterministic Scenarios**: Full stochastic treatment would integrate over scenario distributions.
3. **Static Capital Structure**: Dynamic refinancing responses not modeled.
4. **Tax Effects**: Tax shields on debt ignored (extends to after-tax WACC).

9.3 Extensions

- **Monte Carlo Simulation**: Replace deterministic physical risk parameters with probability distributions.
- **Real Options**: Value of flexibility to switch fuels or retire early.
- **Portfolio Analysis**: Correlation of climate risks across multiple projects.
- **Dynamic Hedging**: Optimal carbon price hedging strategies.

10 Conclusion

We have developed a rigorous mathematical framework for quantifying Climate Risk Premium in project finance. The model demonstrates that:

1. Climate risks (transition and physical) systematically reduce project cash flows.

2. Expected losses translate into higher financing costs through credit spreads and equity premiums.

3. For carbon-intensive assets, CRP can range from 50-200 bps under moderate scenarios to >500 bps under aggressive decarbonization.

4. Properly pricing CRP is essential for:

   - Avoiding asset stranding
   - Accurate project valuation
   - Efficient capital allocation toward climate-resilient investments

The framework is transparent, tractable, and empirically implementable, providing a foundation for integrating climate risks into standard project finance practice.

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A Proofs of Technical Lemmas

A.1 Proof of Monotonicity Properties

Lemma 8. *For fixed physical risk, NPV is monotone decreasing in carbon price:*

$$\tau'_t > \tau_t \; \forall t \Rightarrow NPV(\tau') < NPV(\tau) \tag{42}$$

Proof. Carbon costs enter linearly and negatively in FCF:

$$\mathrm{FCF}_t(\tau') = \mathrm{FCF}_t(\tau) - Q_t \cdot e \cdot (\tau'_t - \tau_t) < \mathrm{FCF}_t(\tau) \tag{43}$$

Discounting preserves inequality, hence $\mathrm{NPV}(\tau') < \mathrm{NPV}(\tau)$. □

A.2 Proof of Convexity Properties

Lemma 9. *Expected loss is convex in carbon price:*

$$\frac{\partial^2 EL}{\partial \tau^2} \geq 0 \tag{44}$$

Proof. Expected loss is linear in carbon costs, which are linear in τ. Hence second derivative is zero, confirming convexity (linear functions are both convex and concave). □

B Numerical Implementation Details

B.1 Algorithm for NPV Calculation

1. **Input**: Plant parameters, scenario $\mathcal{S} = (\mathcal{T}, \mathcal{P})$, discount rate r
2. **Initialize**: $T^* \leftarrow \min(T, T^*_{\mathcal{T}})$
3. **For** $t = 1$ to T^*:
   (a) Compute $\rho_t \leftarrow \rho_0 - \Delta\rho$
   (b) Compute $Q_t \leftarrow C \cdot 8760 \cdot \rho_t \cdot (1 - \delta) \cdot (1 - \lambda)$
   (c) Compute τ_t via interpolation
   (d) Compute $R_t, FC_t, VC_t, FX_t, CC_t, OC_t$
   (e) Compute $\mathrm{FCF}_t \leftarrow R_t - \sum$ costs
4. **Return**: $\mathrm{NPV} = \sum_{t=1}^{T^*} \mathrm{FCF}_t/(1 + r)^t$

B.2 Convergence Properties

The IRR calculation uses Newton-Raphson iteration:

$$r_{n+1} = r_n - \frac{\mathrm{NPV}(r_n)}{\mathrm{NPV}'(r_n)} \tag{45}$$

where:

$$\mathrm{NPV}'(r) = -\sum_{t=1}^{T^*} \frac{t \cdot \mathrm{FCF}_t}{(1 + r)^{t+1}} \tag{46}$$

Convergence is guaranteed if FCF_t changes sign exactly once (Descartes' rule).