Future climate adaptation opportunities and the financing of US investor-owned electric utilities

Martin Ellison* Frederick van der Ploeg† Kexin Wu‡

October 2026

Abstract

We develop a theoretical framework in which the financing of adaptation depends on the prospect of future adaptation opportunities. Firms finance the upfront costs of adaptation through debt and equity, creating opposing financing frictions. Excessive debt raises default risk and weakens incentives for future adaptation, while low reliance on debt increases reliance on costly equity issuance. Our model shows how opposing financing frictions can generate an inverted-U relationship between bond financing and adaptation investment. Using a panel of US investor-owned electric utilities from 2001–2019, we construct measures of adaptation capital and financing capacity from regulatory filings and find an inverted-U relationship between them, consistent with this mechanism.

*University of Oxford and CEPR, martin.ellison@economics.ox.ac.uk
†University of Oxford, University of Amsterdam, and CEPR, rick.vanderploeg@economics.ox.ac.uk
‡University of Oxford, kexin.wu@economics.ox.ac.uk

1 Introduction

Global economic losses from climate-related disasters reached an estimated USD 281 billion in 2023 (OECD, 2024). The private sector is profoundly affected by these shocks, suffering disruptions to revenue, productivity, and profitability that depress investment and employment (Pankratz et al., 2023; Sautner et al., 2023; Somanathan et al., 2021; Ponticelli et al., 2023; Van Reenen and Norris Keiller, 2024; Cevik and Miryugin, 2022; Bettarelli et al., 2025; Berg et al., 2025). In response to these escalating threats, climate adaptation is increasingly recognised as crucial for securing long-term economic stability (Mongelli et al., 2024; Pörtner and Belling, 2022).

Adaptation is defined as the process of adjusting to actual or expected climate conditions, with the aim of moderating or avoiding harm, or exploiting beneficial opportunities (IPCC, 2023). Investment in adaptation yields high economic and social returns, with cost-benefit ratios typically ranging from 1:2 to 1:10 (OECD, 2024). However, there is a large gap between the resources committed to adaptation and the goals set by international frameworks (Pörtner and Belling, 2022). Total adaptation plans fall significantly short of the estimated annual requirement of USD 180 billion, despite the potential to unlock as much as USD 7.1 trillion in net economic benefits over the decade 2020–30, corresponding to a cost-benefit ratio of 1:39 (Buchner et al., 2021).

This paper investigates how corporate finance influences investment in climate adaptation. Inspired by Bodie and Taggart (1978), we recognise that financing investment today can affect firms' incentives to exploit future adaptation opportunities. Adaptation typically involves upfront costs funded by a mixture of equity and bond financing. Bond financing brings the risk of default and bankruptcy, thus weakening firms' incentives to undertake supplementary investments in the future. Since part of the gain from a new profitable investment opportunity accrues to bondholders, shareholders may under-invest even when the project has positive net present value.[1] This debt-overhang problem arises because shareholders bear the investment cost but receive only part of the benefit.

This mechanism is particularly relevant to climate adaptation, where investments unfold over decades and create uncertain future investment opportunities. At the other end of the financing range, greater reliance on costly equity issuance can also constrain adaptation. Building on the Bodie-Taggart mechanism, we show that these opposing financing frictions can generate an inverted-U relationship between bond financing and climate adaptation investment.

[1] However, if the firm can call its old debt before undertaking new investments, shareholders can refinance and capture more of the gains from future projects. This restores investment incentives and raises firm value. Callable debt helps prevent existing creditors from expropriating part of the returns to future investment opportunities. Aivazian and Callen (1980) criticise this, but argue that call provision might eliminate negotiation costs.

We then examine empirically the relationship between corporate finance and climate adaptation in US investor-owned electric utilities. The US electric utility sector is highly capital-intensive, directly exposed to physical climate shocks, and heavily reliant on secured debt. This makes it well-suited to the study of how financing conditions affect adaptation investments. Drawing on industry reports, we define adaptation as the undergrounding of electricity grids and investments in energy storage technologies. To capture firms' financing capacity, we construct a proxy based on the gap between each utility's collateral base and its outstanding bonds. This measures remaining headroom for additional bond financing, rather than the bond-financing share itself. We also combine annual county-level disaster declarations with the Federal Emergency Management Agency's (FEMA) National Risk Index (NRI) to characterise the geographic exposure of utilities through their plant locations and service territories. Our main empirical result is a robust inverted-U relationship between financing capacity and adaptation capital, consistent with this mechanism.

Section 2 reviews the related literature. Section 3 develops our three-period model of financing frictions and climate adaptation investment and presents its analytical and numerical results. Section 4 describes the data, while Section 5 presents empirical evidence from US electric utilities. Section 6 concludes.

2 Related Literature

Our paper relates to several strands of research.

First, we engage with Integrated Assessment Models (IAMs) that model abatement (or mitigation) as emissions reduction and treat adaptation as a flow or stock that offsets climate damages (Lemoine and Traeger, 2014; Barrage and Nordhaus, 2024). We focus on adaptation and build on the distinction between flow adaptation (short-term responses) and stock adaptation (long-term investments in resilient capital) (Felgenhauer and Webster, 2013; de Bruin et al., 2009; Bosello, 2010; Agrawala et al., 2010). A key feature of our framework is path dependency in adaptation opportunities. Drawing on the directed technical change literature (Hémous and Olsen, 2021; Acemoglu et al., 2016; Aghion et al., 2016), we assume that firms become more efficient at using technologies they have previously adopted. As shown by Aghion et al. (2024), early investments then shape the productivity and feasibility of future investments, thus making early financial constraints especially distorting.

Second, we add to empirical work on climate adaptation. Evidence shows gradual adjustment across sectors, including changes in agricultural climate sensitivity (Burke et al., 2024), labour migration responses (Bilal and Rossi-Hansberg, 2023), and country-level financial adjustments to physical risks (Phan and Schwartzman, 2024). Firm-level evidence

on adaptation investment remains limited due to inconsistent definitions and disclosure, with existing studies showing that financing constraints limit investment in green and resilient technologies (Accetturo et al., 2022; Lanteri and Rampini, 2025). High debt burdens further reduce such investment (Guerini and Vona, 2025; De Haas et al., 2024). Survey evidence reveals a gap between exposure to physical risks and protective action, driven by financing barriers (EIB, 2023; Ferrando et al., 2023).

Finally, we connect climate adaptation to corporate finance. Classic frameworks show how financing frictions, such as debt overhang, distort investment (Myers, 1977; Bodie and Taggart, 1978). We extend this logic to climate-related investment. To the best of our knowledge, we are the first to develop the Bodie-Taggart mechanism in a climate adaptation framework.[2] Our framework introduces path dependence in adaptation, with investment today creating opportunities for further adaptation in the future. Debt financing of initial adaptation can then create a debt-overhang problem that distorts investment in these subsequent opportunities. In this sense, Bodie and Taggart's "growth option" becomes a "resilience option". Our paper is also related to OECD (2025), which studies the interaction between climate adaptation spending, debt sustainability, and sovereign default risk, rather than the creditor appropriation of returns to future adaptation that is central to our mechanism.

3 Financing Frictions and Climate Adaptation

We present a three-period model to investigate how financing frictions affect a firm's incentives to invest in climate adaptation technologies that mitigate the effects of adverse environmental shocks. Investments in climate adaptation are assumed to exhibit a high degree of path dependency, making them distinct from investments in physical capital. Our inspiration is the classic corporate finance framework of Bodie and Taggart (1978).

3.1 Timeline

A timeline of the investment decisions is shown in Figure 1. In the first period, the firm has the opportunity to make a discrete investment in climate adaptation that improves its resilience to climate shocks and increases the productivity of its (fixed) physical capital. The indicator variable $A_1 \in \{0, 1\}$ records its decision. If the firm invests in climate adaptation then $A_1 = 1$ and the firm incurs an up-front cost of c. If the firm does not invest then $A_1 = 0$ and there are no associated costs.

In the second period, an additional opportunity to invest in climate adaptation may arise, but only if the firm took advantage of the opportunity to invest in climate adaptation

[2] Rampini and Vishwanathan (2013) highlight the effect of tangible collateral and constrained investment. These corporate finance insights may also apply to the study of climate adaptation.

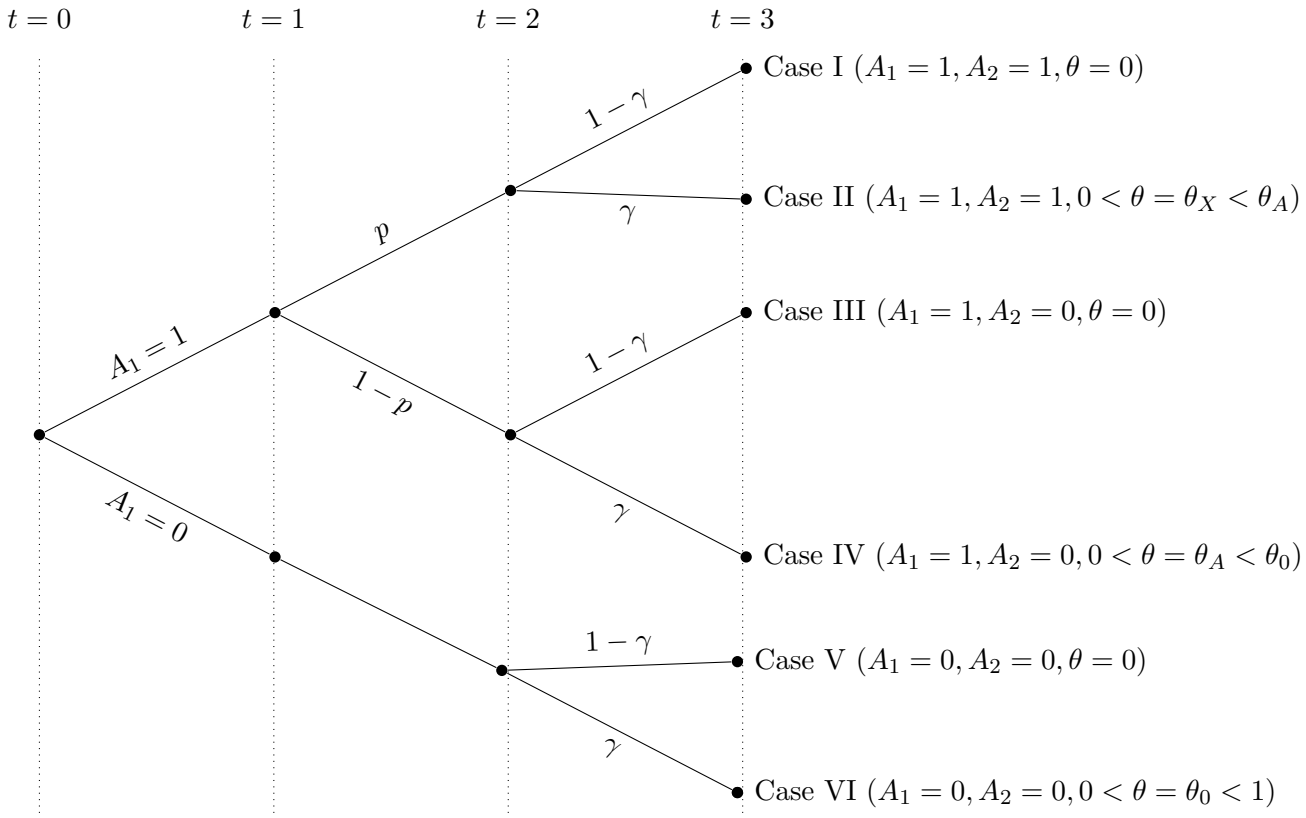


Figure 1: Timeline of Adaptation Investment Opportunities

in the first period. If they did, the additional opportunity arrives with probability p, and is an option to make supplementary investments that further improve resilience to climate shocks and are productive in their own right. If the firm did not invest in climate adaptation in the first period then the opportunity to make supplementary investments never arises. The conditional availability of future investment opportunities reflects our assumption that climate adaptation investments exhibit path dependency. The indicator $A_2 \in \{0, 1\}$ records if the firm makes an additional investment in the second period.

Production takes place in the third period and is subject to uncertainty. With probability γ there is an adverse environmental shock that reduces output, with the proportion of output lost θ depending on how much the firm has invested in climate adaptation in the first and second periods. With probability $1 - \gamma$ there is no adverse environmental shock, in which case there is no loss of output and $\theta = 0$.

Figure 1 thus shows six possible outcomes. If the firm invests in both periods, production takes place either in the absence or presence of an environmental shock (cases I and II). If the second-period investment opportunity does not materialise, the firm enters the production stage having invested only in the first period (cases III and IV). Finally, if the firm does not undertake the initial adaptation investment, there is no subsequent investment opportunity, giving the remaining two outcomes (cases V and VI).

3.2 Environmental Shocks, Adaptation, and Future Output

Output produced in the third period is determined by the productivity of (fixed) physical capital, any climate adaptation investments the firm makes in the first and second periods, and the scale of output losses if there is an adverse environmental shock.

If the firm does not invest in climate adaptation in the first period then output is $\delta_0 \geq 0$ if there is no adverse environmental shock and $(1-\theta_0)\delta_0$ if there is such a shock. If the firm invests in climate adaptation only in the first period, then it improves the productivity of its physical capital and its resilience to environmental shocks, such that output rises to $\delta_A > \delta_0$ if there is no adverse environmental shock and $(1-\theta_A)\delta_A$ if there is, with $\theta_A < \theta_0$ capturing how climate adaptation investment reduces potential output losses.

If the firm invests in climate adaptation in both the first and second periods, it improves the productivity of its physical capital and raises output directly because the second-period supplementary investment is productive in its own right. At a cost of $X > 0$, investing in climate adaptation in the second period increases output to $\delta_A + \delta_X \log(1+X)$ if there is no environmental shock, where $\delta_X > 0$. Whatever the level of X chosen by the firm, the supplementary investment improves the firm's resilience to environmental shocks so that output is $(1-\theta_X)[\delta_A + \delta_X \log(1+X)]$ if there is a shock, with $0 < \theta_X < \theta_A$.

The potential outcomes for output, labelled Cases I-VI, are summarised in Table 1.

Case	Period 1 investment A_1	Period 2 investment A_2	Output loss θ	Output
I	1	1	0	$\delta_A + \delta_X \log(1+X)$
II	1	1	θ_X	$(1-\theta_X)(\delta_A + \delta_X \log(1+X))$
III	1	0	0	δ_A
IV	1	0	θ_A	$(1-\theta_A)\delta_A$
V	0	0	0	δ_0
VI	0	0	θ_0	$(1-\theta_0)\delta_0$

Table 1: Output as Function of Adaptation Investments and the Environmental Shock

3.3 Financing Climate Adaptation

The cost $c > 0$ of making the discrete climate adaptation investment in the first period can be met by equity or bond financing. To capture differences in firms' financing structures, we take η as the exogenous share of the initial adaptation cost financed with bonds, with the remaining fraction $1-\eta$ funded by equity. Thus, η captures variation in reliance on bond financing rather than a financing choice within the model. Equity funding is equivalent to borrowing from shareholders at the risk-free rate ρ, whereas bond financing

involves taking a loan from banks at an interest rate r. Shareholders are assumed to have limited liability, which means that the interest rate charged by competitive risk-neutral banks recognises that the firm may default on its debt. If there is no risk of default, the banks charge the risk-free rate ρ, but otherwise charge the rate $r > \rho$. The supplementary adaptation investments in the second period, if undertaken, are assumed to be completely funded by issuing equity.

3.4 Climate Adaptation Investment Decisions

Firms first have to decide whether to invest in the discrete climate adaptation opportunity available in the first period. If they do so, they also need to decide on the scale of the supplementary adaptation investments in the second period, should the opportunity arise to make them. Adjudication of these adaptation investments depends on their profitability, since shareholders only sanction them if they increase the value of the firm. Without loss of generality, we normalise $\delta_0 = 0$ so that the value of the firm is zero in Cases V and VI when the firm does not invest in the first period. Investment decisions then reduce to assessing whether climate adaptation generates positive shareholder value.

The uncertainty of climate shocks means that the firm may not have sufficient resources to repay its debt. Default is least likely in Case I, when the firm invests in both periods and there is no adverse environmental shock, and most likely in Case IV, when there is no supplementary investment and a shock occurs. The ranking of the intermediate Cases II and III depends on parameter values. We assume that default is more likely in Case II, with similar results if the ranking is reversed. There is no borrowing or default in Cases V and VI.

Very low share of bond financing (η very low)

If the share of bond financing η is very low, the firm can repay its debt even in Case IV, where output is lowest. There is therefore no default and banks lend at the risk-free rate ρ. This no-default regime applies when

$$(1+\rho)^2 \eta c \leq (1-\theta_A)\delta_A, \tag{1}$$

where the left side is the repayment due on bond financing and the right side is output in Case IV. The value of the firm if it makes the initial adaptation investment is

$$\begin{aligned} &p(1-\gamma\theta_X)(\delta_A + \delta_X \log(1+X)) \\ &+(1-p)(1-\gamma\theta_A)\delta_A - (1+\rho)^2 c - p(1+\rho)X, \end{aligned} \tag{2}$$

where p is the probability that the opportunity to make supplementary investment X arises. The first two terms are expected output with and without the supplementary in-

vestment opportunity, while the final two terms are the costs of initial and supplementary investment. Since there is no default, the firm chooses X to maximise

$$(1-\gamma\theta_X)(\delta_A+\delta_X\log(1+X))-(1+\rho)X.$$

yielding

$$X^*=\frac{(1-\gamma\theta_X)\delta_X}{1+\rho}-1, \tag{3}$$

which increases in δ_X but decreases in γ and ρ.[3] Substituting (3) into (2) shows that firm value is independent of η. Equity and bond financing have the same cost in this range, so financing part of the up-front cost with bonds does not constrain investment. The firm undertakes initial adaptation whenever its value is positive.

Low share of bond financing (η low)

At a higher η, the firm defaults only in Case IV. This occurs when

$$(1-\theta_A)\delta_A<(1+r)^2\eta c\leq(1-\theta_X)(\delta_A+\delta_X\log(1+X^*)). \tag{4}$$

Banks therefore charge $r>\rho$. Since Case IV occurs with probability $\gamma(1-p)$, their zero-profit condition is

$$\gamma(1-p)(1-\theta_A)\delta_A+[1-\gamma(1-p)](1+r)^2\eta c=(1+\rho)^2\eta c, \tag{5}$$

where $(1-\theta_A)\delta_A$ is recovered in default. Combining (4) and (5) shows that the lower bound for this regime adjoins the upper bound in (1). Since the firm remains solvent when the second-period opportunity arises, supplementary investment remains X^*.

The value of the firm is

$$\begin{aligned}&p(1-\gamma\theta_X)(\delta_A+\delta_X\log(1+X^*))+(1-p)(1-\gamma)\delta_A\\&-(1-\gamma(1-p))(1+r)^2\eta c-(1+\rho)^2(1-\eta)c-p(1+\rho)X^*,\end{aligned} \tag{6}$$

Combining (6) with (5) and (3) shows that firm value is again independent of η and unchanged from the very-low-η regime. The higher interest rate, which rises with η, is exactly offset by the benefit of limited liability in default.

Medium share of bond financing (η medium)

As η rises further, the firm also defaults in Case II, when it makes supplementary investment but subsequently suffers an adverse environmental shock. Shareholders then bear the cost of supplementary investment but receive its payoff only in the absence of a

[3] We assume that the productivity parameter δ_X is sufficiently large to ensure that $X^*>0$.

shock, reducing the optimum to

$$X = \frac{(1-\gamma)\delta_X}{1+\rho} - 1 \equiv \widetilde{X} < X^*. \tag{7}$$

Supplementary investment is therefore lower than under less debt financing, $\widetilde{X} < X^*$. This default configuration occurs when

$$(1-\theta_X)(\delta_A + \delta_X \log(1+\widetilde{X})) < (1+\widetilde{r})^2 \eta c \leq \delta_A, \tag{8}$$

where $\widetilde{r} > r$ satisfies the bank zero-profit condition

$$\begin{aligned} &p\gamma(1-\theta_X)(\delta_A + \delta_X \log(1+\widetilde{X})) \\ &+\gamma(1-p)(1-\theta_A)\delta_A + (1-\gamma)(1+\widetilde{r})^2 \eta c = (1+\rho)^2 \eta c. \end{aligned} \tag{9}$$

The ranges defined by (4) and (8) overlap because supplementary investment itself affects the resources available to repay creditors in Case II. If shareholders expect solvency in Case II, they choose X^*; if they expect default, debt overhang reduces investment to $\widetilde{X}$. Both equilibria are therefore feasible for some values of η. Where they overlap, we select the value-dominant equilibrium.[4] The firm remains in the low-η regime until the upper bound in (4) binds, after which supplementary investment falls discretely from X^* to $\widetilde{X}$, reducing the value of initial adaptation.

High share of bond financing (η high)

At high η, the firm defaults in all cases except Case I, when it makes supplementary investment and no environmental shock occurs. This regime is defined by

$$\delta_A < (1+\check{r})^2 \eta c, \tag{10}$$

with bank zero-profit condition

$$\begin{aligned} &p\gamma(1-\theta_X)(\delta_A + \delta_X \log(1+\check{X})) \\ &+(1-p)(1-\gamma\theta_A)\delta_A + p(1-\gamma)(1+\check{r})^2 \eta c = (1+\rho)^2 \eta c, \end{aligned} \tag{11}$$

where $\check{r} > \widetilde{r} > \rho$. Supplementary investment remains $\check{X} = \widetilde{X}$, since shareholders still receive its payoff only when there is no environmental shock. Firm value is also unchanged from the medium-η regime. Higher default risk therefore raises the interest rate without

[4] Since $X^* > \widetilde{X}$ and Case II output is increasing in X, the default equilibrium becomes feasible before the solvent equilibrium ceases to be feasible. Let $V(X)$ denote firm value in (2) as a function of supplementary investment. Using the respective bank zero-profit conditions, firm values in the solvent and default equilibria are $V(X^)$ and $V(\widetilde{X})$, respectively. Since X^* uniquely maximises $V(X)$, it follows that $V(X^*) > V(\widetilde{X})$.

further distorting supplementary investment.

To summarise, financing conditions affect adaptation through both an extensive and an intensive margin. The extensive margin is whether the firm undertakes the initial adaptation investment, A_1, which depends on whether it generates positive shareholder value. Conditional on $A_1 = 1$ and the second-period investment opportunity arising, the intensive margin is the scale of supplementary investment. Shareholders choose X^* when they expect to receive the payoff from this investment even if an environmental shock occurs. If the shock instead triggers default, they no longer receive this payoff and supplementary investment falls to $\widetilde{X} < X^*$. Greater reliance on bond financing can therefore reduce not only supplementary adaptation investment, but also the value of the initial investment that creates the opportunity to undertake it.

The default behaviour of the firm is summarised in Table 2.

	Share of bond financing (η)			
Case	Very low	Low	Medium	High
I	No	No	No	No
II	No	No	Yes	Yes
III	No	No	No	Yes
IV	No	Yes	Yes	Yes
V	No	No	No	No
VI	No	No	No	No

Table 2: Default and Share of Adaptation Costs Funded by Bond Financing

3.5 Numerical Example

A numerical example illustrates how financing conditions affect climate adaptation through both the decision to undertake initial adaptation and the scale of subsequent investment. We assume that an adverse environmental shock reduces output by 100%, 90%, or 80%, depending on the firm's adaptation investments (i.e., $\theta_0 = 1$, $\theta_A = 0.9$, and $\theta_X = 0.8$). Output in the absence of first-period adaptation is normalised to zero ($\delta_0 = 0$), while first-period adaptation raises output to $\delta_A = 3.5$ in the absence of an environmental shock, at a cost $c = 2.5$. In our baseline calibration, the productivity of supplementary adaptation investment is $\delta_X = 5.5$, and the second-period investment opportunity and the adverse environmental shock each occur with probability 0.5 ($p = \gamma = 0.5$). The risk-free interest rate is set to $\rho = 0.05$. Values of η range from zero to one, where η is the share of the initial adaptation cost financed by bonds. Alternative values of δ_X capture differences in the productivity of future adaptation opportunities.

Figure 2 shows how the value of initial adaptation and adaptation expenditure change with η. The first panel reports the value of initial adaptation, with the horizontal dashed line at zero marking the threshold above which the firm invests. The other two panels show expected supplementary and total adaptation expenditure.

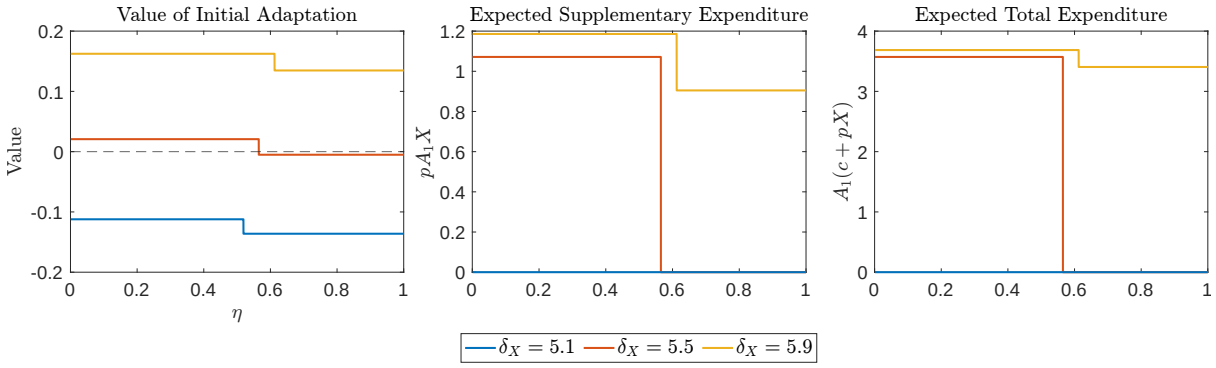


Figure 2: Value of Initial Adaptation and Adaptation Expenditure

The value of initial adaptation depends on the productivity of future adaptation opportunities. For the lowest value of the productivity of supplementary adaptation investment $\delta_X = 5.1$, initial adaptation is unprofitable for all values of η, so that the firm never invests. At the baseline value of $\delta_X = 5.5$, initial adaptation is profitable when the share of bond financing is low. As η rises, however, the firm relies on so much debt that shareholders eventually anticipate default if an environmental shock occurs. This prospect of default creates debt overhang, which reduces the value of future investment opportunities, and makes initial adaptation unprofitable. For the highest productivity of supplementary investment $\delta_X = 5.9$, future opportunities are sufficiently productive for initial adaptation to be profitable for all shares of bond financing η. Even when future opportunities are this productive, debt overhang causes a discrete reduction in supplementary adaptation investment at high levels of bond financing.

Expected supplementary adaptation expenditure is pA_1X, since the second-period opportunity arises with probability p, while expected total expenditure is $A_1(c+pX)$, summing across periods without discounting. For the lowest value of productivity $\delta_X = 5.1$, no adaptation expenditure occurs for any value of η. At the baseline level of productivity $\delta_X = 5.5$, both expenditure measures are positive at low levels of bond financing but fall to zero when the firm ceases to undertake initial adaptation. For the highest value of productivity $\delta_X = 5.9$, both remain positive throughout, although debt overhang causes a discrete fall in supplementary and total expenditure at high levels of bond financing. Future adaptation opportunities therefore affect not only subsequent adaptation investment, but also the firm's incentive to undertake adaptation in the first place.

3.6 Equity Issuance Costs

Equity issue is rarely costless. In addition to direct flotation expenses, equity financing may be hampered by asymmetric information and other capital market imperfections (Myers, 1984; Myers and Majluf, 1984; Fazzari et al., 1988), as well as by constraints on dividend distributions in regulated industries. These frictions may be especially important for climate adaptation investments, whose benefits are uncertain and often materialise only over long horizons.

To capture the cost of issuing equity, we introduce an issuance premium that depends on the share of the initial adaptation investment financed by equity. Let $s = 1 - \eta$ denote this share. If the firm undertakes the investment, it raises sc in equity and incurs a cost $\Omega(s)sc$, where $\Omega(s) \geq 1$ is increasing and convex in the share of equity financing s. Equity issuance costs introduce a second financing friction. When η is low, a large share of the initial investment is financed by equity and issuance costs reduce its value. As η rises (and s falls), these costs fall, but greater reliance on bond financing eventually creates the debt-overhang problem described above. The value of initial adaptation can therefore be low at both ends of the financing range.

For illustration, the issuance premium takes the form $\Omega(s) = e^{0.05s^4}$. We use $\delta_A = 4.6$, $\delta_X = 6.05$, and $c = 3.25$, leaving the remaining parameters unchanged. These values capture the opposing effects of costly equity issuance at low η and debt financing at high η. Figure 3 shows the resulting effects on the value of initial adaptation and adaptation expenditure. The first panel reports the value of initial adaptation, with the horizontal dashed line at zero marking the threshold above which the firm invests. The other two panels show expected supplementary and total adaptation expenditure.

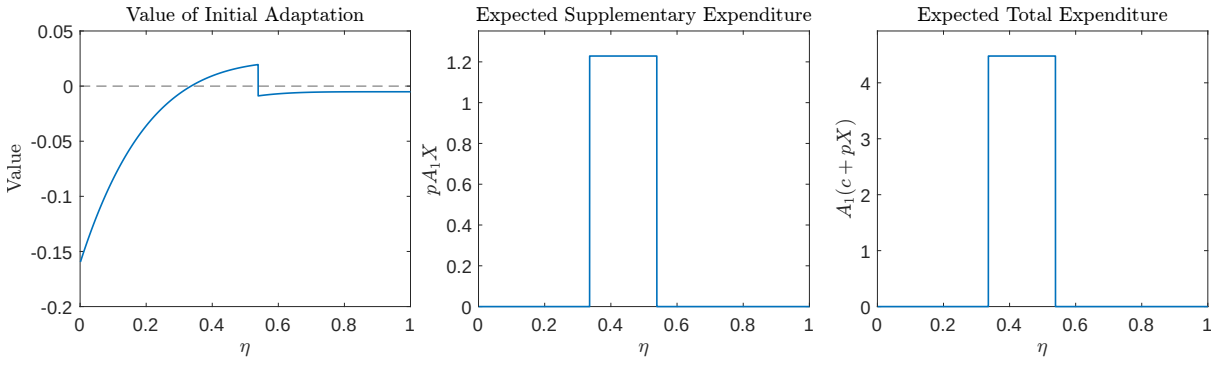


Figure 3: Equity Issuance Costs and Adaptation Expenditure

When η is low, heavy reliance on equity financing makes initial adaptation unprofitable. As η rises, the share of equity financing falls and the value of initial adaptation increases, eventually becoming positive. At higher values of η, the firm has to rely more heavily on debt. Once shareholders anticipate default if an environmental shock occurs, debt

overhang reduces the value of future adaptation opportunities and makes initial adaptation unprofitable again. Expected supplementary and total adaptation expenditure consequently display an inverted-U pattern: both are zero at low η, positive over an intermediate range, and return to zero at high η. Costly equity issuance and debt overhang therefore constrain adaptation at opposite ends of the financing range.

Figure 3 shows the investment response of a single firm with a set of adaptation opportunities and costs. To capture differences across firms, we allow δ_A, δ_X, and c to vary while holding the remaining parameters fixed. This heterogeneity means that firms undertake initial adaptation and encounter debt overhang at different levels of η, so their sharp responses become more gradual when viewed across firms. Figure 4 examines this aggregation using a population of 3,000 firms. We draw δ_A, δ_X, and c independently from normal distributions centred on the calibration above, with standard deviations of 0.25, 0.35, and 0.35, respectively.[5] The first panel reports mean total adaptation expenditure, the second gives the share of firms undertaking initial adaptation, and the final panel reports expenditure conditional on initial adaptation. Individual firms are shown as points in the final panel, with the solid line giving their conditional mean.

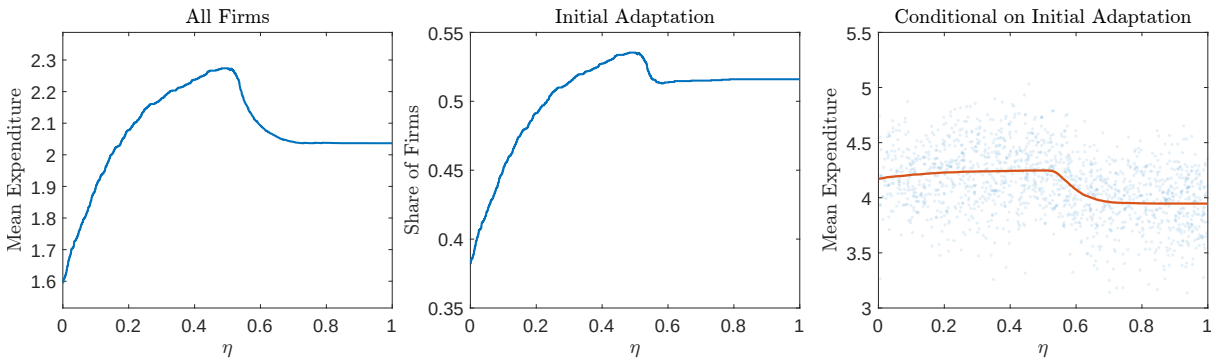


Figure 4: Adaptation Investment with Heterogeneous Firms

Mean adaptation expenditure exhibits an inverted-U relationship with η, the share of bond financing. At low levels of η, the share of firms undertaking initial adaptation rises as reliance on costly equity falls. This extensive-margin response accounts for much of the increase in average expenditure. As η increases further, debt overhang becomes more important and average expenditure begins to fall. Conditional on undertaking initial adaptation, expenditure is relatively stable at low and intermediate values of η, but falls once debt overhang arises. The decline in average adaptation therefore reflects both fewer firms undertaking initial adaptation and lower expenditure among those that continue to invest. Heterogeneity thus turns the discrete investment responses of individual firms into an inverted-U relationship at the population level, with both the extensive and intensive

[5]The distributions are bounded below at $\delta_A = 3.5$, $\delta_X = 4.5$, and $c = 2.0$ to exclude extreme parameter values.

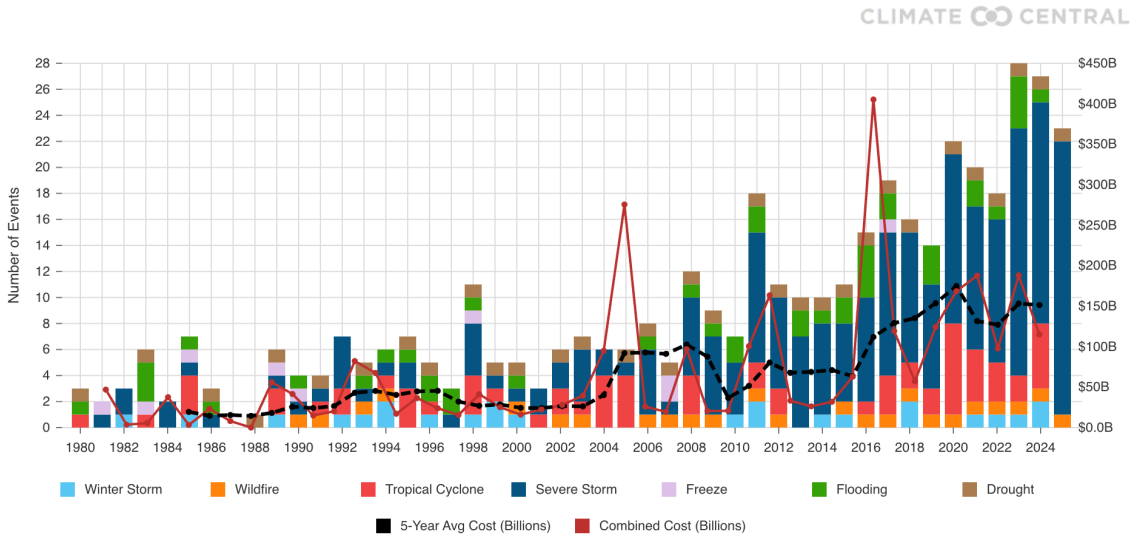
margins contributing to its shape. This inverted-U relationship motivates our empirical analysis of financing capacity and adaptation.

4 Institutional Setting and Data

In this section, we examine the empirical relationship between financing frictions and climate adaptation investment among major US electric utilities. We construct a novel panel dataset by combining financial data from the Federal Energy Regulatory Commission (FERC) with geographic and operational plant-level data from the US Energy Information Administration (EIA). Measures of physical climate shocks and risks are obtained from the Federal Emergency Management Agency (FEMA). Consistent with the analysis in Section 3, we find a robust inverted-U relationship between utilities' financing capacity and their accumulated stock of adaptation capital.

4.1 Climate Adaptation in the United States

The cost of major climate-related disasters has grown substantially in the United States over the past four decades. As reported by the National Oceanic and Atmospheric Administration (NOAA, 2025) in Figure 5, inflation-adjusted losses from weather and climate events were higher in 2010–2019 than in any previous decade. The higher frequency and severity of these events, particularly severe storms and tropical cyclones, has increased the need for private sector investment in climate adaptation alongside public spending on environmental resilience.



The history of billion-dollar disasters in the United States each year from 1980 to 2025, showing event type (colors), frequency (left-hand vertical axis), and cost (right-hand vertical axis) adjusted for inflation to 2025 dollars.

Figure 5: US Weather and Climate Disasters 1980-2025, (NOAA, 2025)

Evidence on how private-sector firms finance adaptation is nonetheless scarce, especially compared with the literature on financing emissions mitigation, for at least two reasons. First, unlike greenhouse gases, which have a broadly accepted accounting framework, there is no uniform sectoral definition of adaptation investment. This makes it difficult to identify adaptation spending in firm-level capital expenditure data. Second, due to the place- and technology-specific nature of adaptation, cross-sector comparisons are difficult. As a result, empirical work has tended to rely on case studies, survey evidence, or aggregate national accounting estimates, providing limited insight into firm-level financing constraints.[6] We take a different approach by focusing on a single regulated industry in which adaptation investment and its financing are unusually well documented. This allows us to examine how financing frictions affect the scale and timing of private-sector adaptation investment.

4.2 Investor-Owned Electric Utilities

US Investor-Owned Electric utilities (IOUs) are privately owned, for-profit corporations that operate as regulated monopolies within an exclusive, state-granted service territory. Together they serve around 220 million Americans (EEI, 2020). The US utility sector is a promising setting in which to study the financing of climate adaptation because of the nature of adaptation investment and the way it is financed.

4.2.1 Climate Adaptation Investment

IOUs are capital intensive, with physical infrastructure such as substations, transmission towers, and wooden distribution poles directly exposed to climate-related risks. Severe weather has repeatedly caused major outages to the US electricity grid. The Edison Electric Institute (EEI), the association representing US investor-owned electric companies, reports that lightning, storms, and wind-blown vegetation accounted for about two-thirds of all outage minutes reported by its member utilities in 2008 (Hall, 2009). Extreme events such as storms and floods can also destroy physical capital, an important channel through which climate risks reduce firm productivity (Lepore and Fernando, 2023). The combination of substantial capital needs and direct exposure to climate shocks makes the utility sector well suited for studying the financing of adaptation.

EEI has developed a taxonomy of "Adaptation, Hardening, and Resilience" (AHR) investments that maps onto the industry's capital expenditure categories (EEI, 2025b). Examples include undergrounding distribution lines, elevating or relocating transformers

[6] A recent exception is Duffy (2026), who uses machine learning to construct an adaptation expenditure measure from government budget documents and finds that adaptation spending is positively associated with sovereign credit ratings. Cyclone shocks increase sovereign default risk, but less so in countries with greater adaptation investment. The quantitative analysis also points to an "adaptation trap", whereby higher sovereign risk reduces adaptation investment, increasing future disaster losses and further reinforcing sovereign risk. Our analysis instead focuses on corporate default.

in flood-prone areas, and reinforcing transmission structures in high-wind zones. According to EEI's 2025 member-company survey, AHR investments account for 21 per cent of transmission and 33 per cent of distribution capital expenditure (EEI, 2025b). Of the $178.2 billion invested by EEI member companies in 2024, more than $30 billion was allocated to AHR projects in transmission and distribution (EEI, 2025a).

Converting overhead transmission and distribution lines to underground systems is a widely studied form of AHR investment. DOE identifies targeted undergrounding as reducing exposure to lightning, tree, and storm damage (DOE, 2016), while it is increasingly used to reduce wildfire ignition risks (Cal. Pub. Util. Code §8388.5, 2022). Evidence points to substantial resilience gains. During Hurricane Irma in 2017, 4 per cent of Florida Power & Light's underground lines experienced outages, compared with 24 per cent of its unhardened overhead lines. Underground lines nevertheless remain vulnerable to flooding and storm surge and can take longer to repair (DOE, 2024).

Undergrounding also illustrates the substantial financing needs of adaptation capital. Its cost is typically five to ten times that of overhead construction (Hall, 2009). Recent programs report costs ranging from about $0.15 million per mile for rural lines to roughly $3 million in California's high fire-threat areas (DOE, 2024). Individual programs can require substantial investment. In 2012, Potomac Electric Power Company (Pepco) proposed undergrounding six distribution feeders in Maryland at a cost of $151 million (DOE, 2016). At scale, North Carolina's Public Staff estimated that undergrounding the distribution lines of the state's three IOUs would cost $41 billion, nearly six times the net book value of their distribution assets (Hall, 2009). These investments require large upfront outlays, while costs are recovered from ratepayers only gradually.

4.2.2 Financing Adaptation Investment

Investor-owned utilities retain considerable discretion over adaptation capital spending, including which measures to pursue and at what pace (Lazar, 2016). This discretion operates within regulatory oversight. Large generation projects and, in many states, new transmission lines require ex-ante approval, while other major investments may also be pre-approved before construction begins (Lazar, 2016). Completed assets may then undergo prudence and used-and-useful review before entering the rate base (Lazar, 2016).[7]

For adaptation specifically, several states require or allow utilities to file dedicated wildfire mitigation, storm protection, or resilience plans (Cal. Pub. Util. Code §8386, 2025). Utilities propose the measures, projects, and timelines, while regulators review the plans

[7]The rate base comprises long-lived utility investments that were prudently incurred and are used and useful in providing service. It is generally measured as plant in service at original cost net of accumulated depreciation, with adjustments for working capital, deferred taxes, and other commission-approved items. Utilities are authorised to earn an allowed rate of return on this base.

and may impose conditions such as cost caps (CPUC, 2024). Participation is not always mandatory: Texas permits but does not require resilience plans (Tex. Util. Code §38.078, 2023), while California's expedited undergrounding program is optional for large utilities (Cal. Pub. Util. Code §8388.5, 2022). Utilities may also retain flexibility over the pace of investment while plans are under review. Pacific Gas and Electric Company (PG&E), a large California IOU, has proposed undergrounding 307 miles of lines annually until its ten-year plan is approved (PG&E, 2025). Regulatory oversight therefore constrains, but does not determine, utilities' adaptation investment decisions.

Because an IOU cannot unilaterally raise prices to fund adaptation, its ability to invest depends on access to external finance, particularly when investment needs exceed internal cash flow. Industry-wide, capital expenditure and dividends have persistently exceeded operating cash flow. Post-dividend free cash flow was negative every year from 2005 to 2011, with the shortfall financed mainly through new long-term debt (EEI, 2012). More recently, PG&E expects capital expenditure, debt maturities, and dividends to exceed operating cash flows, with the shortfall financed primarily through capital and credit markets (PG&E, 2025).

Two features of utility regulation make this financing need particularly important. First, there is a structural mismatch between when investment costs are incurred and recovered from ratepayers. Under standard cost-of-service regulation by state Public Utility Commissions (PUCs) or FERC, utilities earn an authorised return on prudently invested capital through the rate base (Schumacher and Hess, 2010). This provides for eventual cost recovery, but not the funds needed to invest. Costs are recovered gradually over the asset's life, and in most states financing costs during construction are added to the rate base only once the asset enters service (Lazar, 2016). Utilities must therefore secure external finance to bridge the gap between upfront costs and subsequent rate recovery.

A second friction arises from regulatory lag, the delay between a change in a utility's costs and its recognition in rates (Lazar, 2016). EEI uses the time from rate case filing to decision as a proxy for the delay between capital expenditure and recovery (EEI, 2012). On this measure, electric rate reviews averaged about eight to eleven months each year over 2010–2019 (EEI, 2020).[8] The full delay is longer because costs are typically incurred before a case is filed, while the use of historical cost data in setting rates can add further delay (EEI, 2012). Outcomes are also uncertain: over 2010–2019, authorised returns on equity were on average 0.5–0.9 percentage points below those requested by utilities each year (EEI, 2020).

These features mean that even prudent investments are not necessarily recovered immedi-

[8] Annual figures are averages of the quarterly values reported in EEI (2020), based on S&P Global Market Intelligence / Regulatory Research Associates data. This method reproduces EEI's reported 2020 average of 8.93 months.

ately, and utilities may earn less than their authorised return before those costs are fully recovered. Utilities must finance these gaps through their balance sheets, making their financing structure potentially important for large, upfront adaptation investments.[9]

4.2.3 First Mortgage Bonds

US investor-owned electric utilities have long relied on secured borrowing, primarily through first mortgage bonds (FMBs) (Terrell, 2022). These bonds are secured against the operating utility's property, so the amount of additional debt a utility can issue depends on the value of its assets relative to bonds already outstanding (Terrell, 2022; PPL Electric, 2026). For example, PPL Electric can issue bonds against up to two-thirds of qualifying property, while secured debt across the sector is typically limited to 70 per cent or less of the asset base (PPL Electric, 2026; James, 2025). Borrowing capacity therefore falls as assets depreciate or outstanding bonds absorb available collateral, and rises as utilities add new assets or retire existing bonds (Terrell, 2022).

Secured borrowing can provide utilities with a relatively low-cost source of external finance. Equity typically requires a higher return than debt, and because equity returns are taxable while interest is deductible, a higher equity share raises the revenue requirement borne by customers (Lazar, 2016). Secured utility bonds are typically rated AA or A, and secured bondholders have been repaid in full even in rare utility bankruptcies (James, 2025). FMBs can therefore play an important role in financing investment.

The reliance on mortgage bonds creates a direct link between a utility's balance sheet and its capacity to finance adaptation. Because new issuance depends on collateral not already backing existing bonds, utilities with more unpledged property have greater scope to raise additional debt. Our empirical strategy captures this variation using available collateral relative to outstanding bonds. We then examine how this financing capacity affects the scale and timing of climate adaptation investment.

4.3 Data and Construction of Variables

4.3.1 Datasets

We build an annual panel of US investor-owned electric utilities from 2001 to 2019, combining data from FERC and EIA annual reports with FEMA disaster declarations. Specifically, we use:

– FERC Form 1 Schedules 110, 114, and 300, which provide data on assets and

[9]Mechanisms that reduce regulatory lag, including construction work in progress in the rate base, forecasted test years, formula rate plans, and cost trackers, have expanded across states (Lazar, 2016). Some commissions have reduced allowed returns on equity where these mechanisms shift risk from utilities to customers (EEI, 2012). The underlying financing need nevertheless remains because utility investments are recovered over long horizons.

liabilities, operating income and revenues, outstanding bonds and long-term debt, retained earnings, cash, and interest charges.

- FERC Schedule 204, which reports the annual starting balance, additions, retirements, and ending balance of transmission and distribution (T&D) capital in service.[10]

- EIA Forms 860 and 861, which provide plant locations and utility service territories at the county level.

- FEMA disaster declarations and the National Risk Index, which provide county-level measures of major natural disasters (FEMA, 2026) and composite physical climate risk (FEMA, 2025), respectively.

All FERC and EIA source tables are standardised by the Public Utility Data Liberation (PUDL) project (Selvans et al., 2025).[11] We use the `utility_id_pudl` identifier to merge FERC and EIA filings, including EIA-861 service-territory records, into a single utility-year panel. We use source data beginning in 1996, so that five-year backward moving averages can be constructed from the beginning of the estimation window where the underlying data are available. The estimation window is therefore 2001–2019.

4.3.2 Defining the Sample

Merging the finance, plant-in-service, and climate data yields a panel of 5,865 utility-years covering 350 FERC-reporting entities over 1996–2024. We exclude 142 entities that are not investor-owned electric utilities, including generation-and-transmission and distribution cooperatives, independent system operators and regional transmission organisations (ISOs/RTOs), independent power producers, generation-only or transmission-only subsidiaries, non-operating holding companies, a small number of water and municipal utilities, and entities with misattributed or missing filings.

We next remove 55 utilities (523 utility-years) that never report a positive bonds-to-assets ratio. Restricting the remaining data to the 2001–2019 estimation window leaves 146 utilities and 2,447 utility-years. Of these, 9 utilities (110 utility-years) never report a positive adaptation capital stock and are removed.[12] Finally, we require at least three sample years per utility, removing a further 5 utilities (6 utility-years). Annual flows and

[10] The FERC codes for adaptation T&D capital and other relevant assets are available in Appendix A.1.2.

[11] Details of the raw data sources are available in Appendix A.1. FERC financial data are available back to 1994, but EIA-861 service-territory data, which are required to construct the climate-exposure measures, begin in 2001.

[12] Schedule 204 does not allow us to distinguish genuine zeros in adaptation capital from missing or misclassified accounts. We therefore exclude utilities for which no positive adaptation capital stock is observed during the sample period.

ratios are winsorised at the 1st and 99th percentiles before constructing moving averages. The resulting panel contains 2,331 utility-years for 132 utilities across 48 states over 2001–2019, with an average of 17.7 years per utility.

4.3.3 Measuring Financing Capacity

FERC Form 1 reports a utility's outstanding bonds and the depreciated book value of its utility plant. Because a utility's plant serves as collateral for first mortgage bonds, the value of its plant net of outstanding bonds provides a measure of its remaining borrowing capacity. For utility i in year t, we define

$$\text{Financing Capacity}_{i,t} = \left(\frac{\text{Net Utility Plant} - \text{Bonds}}{\text{Total Assets}} \right)_{i,t}.$$

The components of this measure are taken from FERC Form 1 Schedule 110.[13] A higher value indicates greater headroom to raise additional secured debt. In the empirical analysis, we use a five-year backward moving average based on the preceding five years, requiring at least four non-missing observations. Using past values separates the measurement of financing conditions from the current adaptation capital stock and reduces noise from year-to-year movements in the balance sheet. The five-year horizon also reflects the multi-year period over which large adaptation projects are financed and undertaken.[14]

As an external check on our measure, we compare financing capacity with S&P credit ratings for the parent holding companies of 130 of the 132 utilities in our panel, using EEI's quarterly ratings compilations (EEI, 2026). Because ratings are reported at the parent level while financing capacity is measured for operating subsidiaries, this comparison provides an external validation rather than a direct measure of subsidiary credit quality. Financing capacity is nevertheless positively correlated with parent credit quality, both across the sample and after accounting for differences across parent companies. Mean financing capacity also declines monotonically across S&P rating categories, from 0.52 for subsidiaries of parents rated A or above to 0.38 for those rated BB or below. These patterns provide independent support for interpreting financing capacity as a measure of utilities' ability to raise additional debt.

Financing capacity is not a direct empirical measure of η, the share of adaptation costs financed with bonds in the model. The two nevertheless have a natural inverse interpretation in terms of debt reliance. Higher η represents greater reliance on bond financing. By contrast, lower financing capacity indicates that outstanding bonds have absorbed more of the collateral available to support secured debt. Low financing capacity there-

[13] Net utility plant is the book value of a utility's infrastructure assets after accumulated depreciation, amortization, and depletion. Further details on the FERC Form 1 accounting variables are provided in Appendix A.1.2.

[14] Further details of variable construction are provided in Appendix A.1.4.

fore corresponds to the debt-intensive side of the model, where debt overhang constrains adaptation, while high financing capacity corresponds to the less debt-intensive side, where costly equity financing can constrain investment. Because this inverse interpretation reverses the financing axis without changing the inverted-U shape, it motivates our empirical specification in financing capacity.

4.3.4 Stock of Adaptation Capital

FERC Schedule 204 reports the year-end balance of each utility's plant in service. We define the adaptation capital stock as the sum of underground conduit, underground conductors and devices, and energy storage equipment for transmission and distribution. These correspond to FERC accounts 357 and 358 for transmission, 366 and 367 for distribution, and 351 and 363 for energy storage. We also construct an above-ground (overhead) T&D capital stock, comprising overhead conductors and devices, poles and fixtures, and towers and fixtures (accounts 354–356 and 364–365).

We express the capital stocks in constant 2019 dollars. Since the stocks comprise investments made in different years, we account for the price level at the time each investment was made rather than applying a single deflator to the entire stock. For each uninterrupted reporting spell, we convert the initial balance to real terms and then add subsequent annual changes at the price level prevailing in each year. These changes are measured from reported year-end balances and already incorporate asset retirements. This approach provides a vintage-consistent measure of the real capital stock.[15]

4.3.5 Exposure to Climate Risk

We measure climate exposure across two geographic footprints. The *combined* footprint includes counties containing a utility's generation plants and counties in its service territory; the *territory-only* footprint includes only service-territory counties. The latter provides a narrower geographic measure but has shorter time coverage because service-territory data begin in 2001. To capture acute weather shocks, we count the number of FEMA-declared major weather disasters across the counties in each footprint. We use the five-year backward moving average of this measure in the empirical analysis.[16]

Underlying physical climate risk is measured using FEMA's National Risk Index (NRI). The NRI provides a time-invariant county-level composite measure of expected annual loss, social vulnerability, and community resilience. We average the NRI score across

[15]Nominal values are deflated using annual averages of the BLS CPI-U (all items, series CUUR0000SA0). Results are similar when using nominal balances or deflating each year's entire ending balance by that year's price level. Further details of the construction are provided in Appendix A.1.4.

[16]FEMA-declared natural disasters include droughts, floods, freezes, severe and ice storms, tropical storms, hurricanes, wildfires, winter storms, tornadoes, coastal storms, earthquakes, tsunamis, volcanic eruptions, typhoons, and snowstorms.

counties within each utility's footprint and define a high-risk indicator equal to one when this average lies in the top quartile of the distribution. Although county-level NRI scores are time invariant, a utility's classification can change as its geographic footprint changes over time. As with acute weather shocks, we use the five-year backward moving average of this indicator in the empirical analysis.

4.3.6 Other Financial Variables

The financial controls are constructed from FERC Form 1 and include total assets, the cash ratio (cash to total assets), operating revenues, interest coverage (operating income relative to interest charges), and long-term leverage (the ratio of long-term debt to total assets). Total assets and operating revenues are expressed in constant 2019 dollars. The underlying ratio variables are winsorised at the 1st and 99th percentiles before constructing the five-year backward moving averages used in the empirical analysis. Interest coverage is additionally capped at 15 to limit accounting artefacts arising from near-zero interest charges.

4.4 Descriptive Statistics

Table 3 reports summary statistics for the key variables in our panel of 132 utilities and 2,331 utility-years over 2001–2019. Financial and climate variables are shown as five-year backward moving averages. Average financing capacity is 0.45, with a standard deviation of 0.14; roughly a quarter of utility-years are classified in the highest NRI-risk quartile under either footprint. Sample sizes vary across variables because of the moving-average requirements and gaps in the underlying FERC and EIA data. The full sample used in our main specification contains 1,424 utility-years across 110 utilities, with further sample comparisons provided in Appendix A.2.

Figure 6 shows that the evolution of adaptation capital differs systematically with utilities' exposure to climate risk. The left panel plots the real adaptation capital stock by NRI risk quartile. Utilities in the highest-risk quartile hold substantially more adaptation capital throughout the sample, with the gap widening over time as their stock grows more rapidly. The right panel compares annual additions to adaptation and overhead T&D capital. The two series move closely together in earlier years, but overhead investment grows more rapidly from around 2009 onwards. Adaptation investment therefore does not simply mirror broader trends in T&D investment.

Variable	N	Mean	Median	Std. dev.
Financing capacity	1882	0.45	0.45	0.14
Total assets, log real	2285	22.1	22.2	1.4
Cash ratio	1930	0.0024	0.0016	0.0030
Long-term leverage	2274	0.28	0.29	0.07
Interest coverage	2281	2.74	2.60	1.02
Operating revenues, log real	2288	21.8	21.9	1.3
Adaptation capital stock, log real	2331	19.6	19.7	1.7
Combined climate shock count	2015	12.5	6.2	15.0
Combined NRI high	2000	0.237	0.000	0.416
Territory climate shock count	1618	14.4	8.3	16.1
Territory NRI high	1603	0.248	0.000	0.430

Notes: Except for the adaptation capital stock, variables are five-year backward moving averages requiring at least four non-missing observations. Sample sizes vary because of this requirement and missing underlying data.

Table 3: Summary Statistics

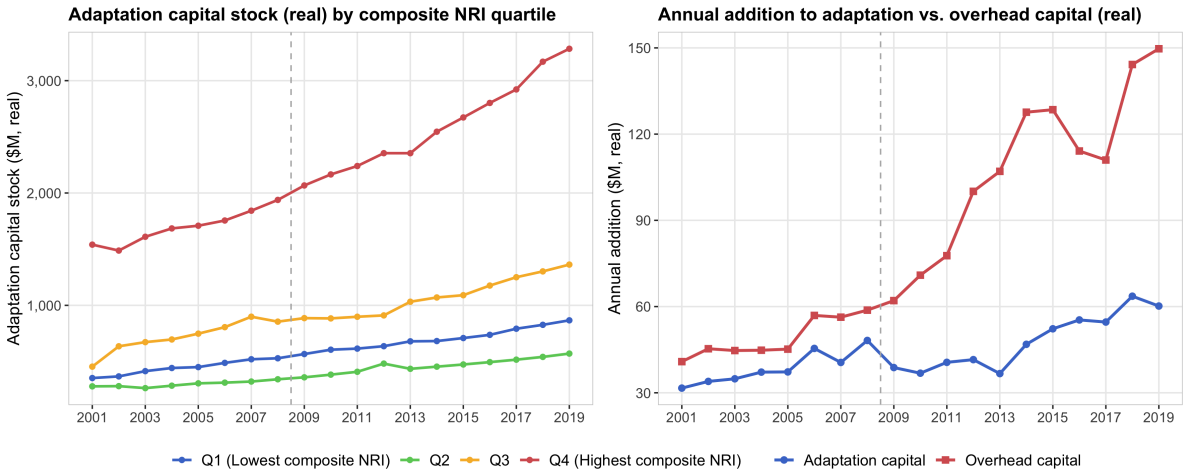


Figure 6: Adaptation Capital Stocks and Investment

5 Empirical Evidence

The model generates a non-monotonic relationship between bond financing and adaptation. Empirically, we examine whether a corresponding relationship arises with financing capacity. We first estimate this relationship while accounting for utilities' financial characteristics and exposure to climate risk, before examining the resulting inverted-U pattern and its robustness.

5.1 Empirical Specification

The relationship between financing capacity and adaptation capital is estimated as:

$$\log A_{i,t} = \alpha_s + \lambda_t + \beta_1 F_{i,t} + \beta_2 F_{i,t}^2 + \beta_3 D_{i,t} + \beta_4 R_{i,t} + \gamma' Z_{i,t} + \varepsilon_{i,t}.$$

where $A_{i,t}$ is the real adaptation capital stock of utility i in year t, and $F_{i,t}$ is its financing capacity. The linear and quadratic terms in financing capacity allow for a non-monotonic relationship consistent with the mechanism in the model. $D_{i,t}$ measures exposure to recent weather shocks, while $R_{i,t}$ captures underlying physical climate risk. Both are constructed for the combined and territory-only footprints described in Section 4.3.5. The vector $Z_{i,t}$ contains the financial controls: total assets, cash ratio, operating revenues, interest coverage, and long-term leverage.[17] Total assets and operating revenues enter in logarithms. Except for adaptation capital, all time-varying variables are five-year backward moving averages based on information preceding year t.

State fixed effects, α_s, absorb persistent differences in regulatory and other conditions across states, while year fixed effects, λ_t, capture common macroeconomic and industry-wide variation. Standard errors are clustered at the utility level.

5.2 Empirical Results

Table 4 presents the regression estimates. Columns (1)–(2) exclude climate controls, columns (3)–(4) use the combined climate footprint, and columns (5)–(6) use the territory-only footprint. Across all specifications, the linear term in financing capacity is positive and significant, while the quadratic term is negative and significant. This provides consistent evidence of an inverted-U relationship between financing capacity and adaptation capital. The implied turning points range from 0.46 to 0.61 and are statistically significant at the 1% level throughout.

[17] Long-term leverage is distinct from both financing capacity and the model's η. Leverage measures the utility's total long-term debt relative to total assets, whereas financing capacity measures collateral available relative to outstanding bonds. Theoretical η is instead the share of a particular adaptation investment financed with bonds. Controlling for leverage therefore helps distinguish available secured borrowing capacity from the utility's overall indebtedness.

	No climate controls		Combined footprint		Territory-only footprint	
	(1)	(2)	(3)	(4)	(5)	(6)
Financing capacity	3.06**	2.59*	4.80***	4.00***	4.74***	3.63***
	(1.31)	(1.32)	(1.31)	(1.08)	(1.37)	(1.16)
Financing capacity^2	−2.52*	−2.36*	−4.17***	−4.21***	−3.94**	−3.92***
	(1.51)	(1.37)	(1.48)	(1.15)	(1.52)	(1.22)
Log assets	0.36**	0.50*	0.56***	0.88***	0.63***	0.88***
	(0.18)	(0.25)	(0.19)	(0.18)	(0.20)	(0.20)
Cash ratio	19.32	3.79	0.28	1.79	5.73	−2.92
	(15.59)	(16.86)	(14.86)	(13.88)	(15.19)	(13.94)
Log operating revenues	0.77***	0.55**	0.50**	0.10	0.43**	0.09
	(0.18)	(0.26)	(0.19)	(0.19)	(0.20)	(0.20)
Interest coverage	−0.07	−0.04	−0.05	0.12***	−0.09	0.08**
	(0.05)	(0.08)	(0.07)	(0.04)	(0.07)	(0.03)
Long-term leverage	0.55	−0.35	0.38	−0.07	0.16	−0.53
	(0.84)	(0.81)	(0.75)	(0.55)	(0.80)	(0.68)
Combined shock count			−0.008**	−0.004*		
			(0.004)	(0.002)		
Combined NRI high			0.68***	0.72***		
			(0.13)	(0.12)		
Territory shock count					−0.006*	−0.004*
					(0.004)	(0.002)
Territory NRI high					0.72***	0.71***
					(0.14)	(0.14)
Observations	1601	1522	1431	1424	1100	1099
R^2	0.84	0.93	0.88	0.95	0.90	0.96
Year FE	X	X	X	X	X	X
State FE		X		X		X
Turning point	0.61***	0.55***	0.58***	0.48***	0.60***	0.46***

Notes: The dependent variable is the log of the real adaptation capital stock. Except for the dependent variable, time-varying variables are five-year backward moving averages. Utility-clustered standard errors are in parentheses. $*p < 0.1$, $**p < 0.05$, $***p < 0.01$.

Table 4: Financing Capacity and Adaptation Capital

Among the financial controls, log assets enters positively and significantly across all specifications, consistent with larger utilities holding larger stocks of adaptation capital. Log operating revenues is also positive and significant in columns (1)–(3) and (5), but loses significance when state fixed effects and climate exposure are jointly included in columns

(4) and (6). Among the climate measures, recent disaster exposure enters negatively, suggesting that weather shocks do not translate immediately into greater adaptation capital and may instead disrupt or delay investment. By contrast, the high-NRI indicator enters positively and significantly, consistent with utilities facing greater underlying physical climate risk holding larger adaptation stocks. These patterns are similar across the two climate footprints despite the smaller territory-only sample, indicating that the results are not driven by the inclusion of generation-plant counties in the combined footprint.

5.3 Interpreting and Testing the Inverted-U Relationship

To examine the variation underlying the regression estimates, Figure 7 plots the partial residuals from column (4) of Table 4 against financing capacity, together with the estimated quadratic relationship. The partial residuals net out all other regressors, while the quadratic traces the inverted-U implied by the regression, with a turning point at 0.475. The figure also highlights observations that deviate substantially from the model. Red observations have standardised regression residuals below -2.5. Among utility-years with financing capacity above 0.65, orange observations have residuals above 1.5, while blue observations have residuals below -1.5. These criteria identify 40 of the 1,424 utility-years, concentrated in ten utilities.

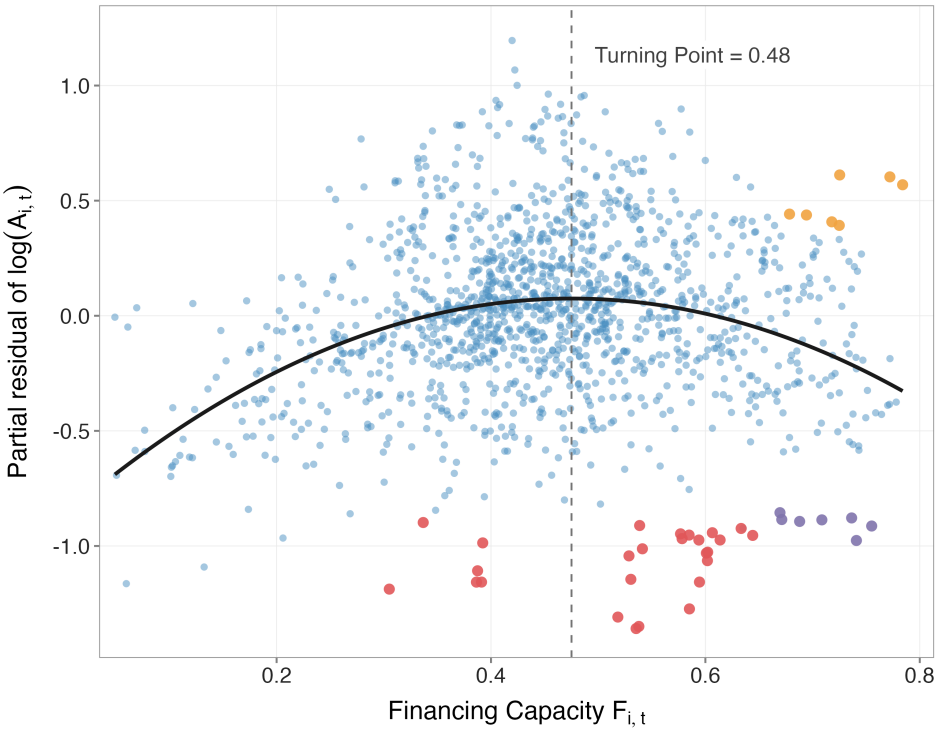


Figure 7: Partial Residual Plot of Column (4) in Table 4

The seven purple outliers come from two utilities that lie persistently below the fitted

curve. Superior Water, Light and Power Company, a small ALLETE subsidiary that also provides gas and water service in Superior, Wisconsin, has standardised residuals between −2.1 and −3.1 throughout 2005–2019. It is classified as a purple outlier in 2011–2014, when its financing capacity exceeds 0.65, and accounts for 11 of the 26 red outliers in other years. These low residuals may partly reflect the inclusion of non-electric utility plant on its balance sheet, which causes our scale controls to overstate the size of its electric network. Other red outliers coincide with identifiable investment programmes. Wisconsin Public Service Corporation, for example, is a red outlier in 2011–2014, before its System Modernisation and Reliability Project converted rural overhead distribution lines to underground over 2012–2021 (DOE, 2024). As these conversions accumulate, its adaptation capital grows by roughly 14–25 per cent per year from 2014 onward, bringing its residual closer to the fitted relationship and reaching −0.9 by 2019.

The seven orange outliers come from three utilities and show a different pattern. CenterPoint Energy Houston Electric (2017–2019) and El Paso Electric (2018–2019) have increasingly positive residuals as their financing capacity moves beyond the estimated turning point. Their adaptation capital nevertheless continues to grow at rates similar to earlier years. This persistence suggests that these observations may reflect utility-specific investment patterns rather than a sharp response to contemporaneous financing capacity.

Table 5 tests whether the inverted-U relationship is driven by the unusual observations highlighted in Figure 7. We re-estimate column (4) of Table 4 after separately excluding all 40 outliers, Superior Water, Light and Power alone, all utilities with at least one outlier, and the red outliers only. A final specification restricts the sample to 2005 onward. Across these samples, the financing-capacity coefficients remain significant at the 1% level and close to the full-sample estimates. The implied turning point also remains within a narrow range of 0.46–0.49, compared with 0.48 in the full sample. The inverted-U relationship is therefore not driven by the unusual observations highlighted in Figure 7.

Sample	N	Financing capacity	Financing capacity^2	Turning point
Full sample	1424	4.00***	−4.21***	0.48***
		(1.08)	(1.15)	
Exclude all outliers	1384	3.68***	−3.81***	0.48***
		(0.96)	(1.00)	
Exclude Superior Water, Light and Power	1409	3.34***	−3.38***	0.49***
		(0.94)	(0.95)	
Exclude utilities with any outlier	1306	3.65***	−4.00***	0.46***
		(1.07)	(1.07)	
Exclude red outliers	1398	3.85***	−4.00***	0.48***
		(0.97)	(1.01)	
2005 onward	1123	3.57***	−3.78***	0.47***
		(1.15)	(1.23)	

Notes: Utility-clustered standard errors are in parentheses. $*p < 0.1$, $**$ $p < 0.05$, $***p < 0.01$.

Table 5: Robustness to Outliers and Sample Restrictions

6 Conclusions

Climate adaptation is increasingly recognised as essential for managing the economic consequences of climate change. Yet despite high estimated social returns, adaptation investment remains persistently below what is needed. We argue that this reflects not only the availability of finance, but also the interaction between financing choices and the dynamic nature of adaptation itself. Adaptation often creates future adaptation opportunities: investments undertaken today increase the productivity, feasibility, and value of investments tomorrow. Climate adaptation thus generates a resilience option.

We develop a model in which firms finance initial adaptation through a combination of debt and equity. While debt helps meet the upfront cost of adaptation, it also creates the possibility of future financial distress. When some of the gains from subsequent adaptation investments accrue to creditors, shareholders have weaker incentives to undertake them, creating a debt-overhang problem analogous to that identified by Bodie and Taggart (1978). In our setting, excessive reliance on debt can therefore constrain not only current adaptation but also firms' incentives to exploit future resilience opportunities.

This debt-overhang mechanism constrains adaptation when firms rely heavily on debt. At the other end of the financing range, low reliance on debt leaves firms more dependent

on costly equity issuance, which can also constrain investment. Adaptation is therefore greatest at intermediate financing conditions. Greater reliance on bond financing initially reduces costly equity financing, but beyond a point debt overhang begins to dominate. The model thus generates an inverted-U relationship between financing conditions and adaptation investment.

We examine this relationship using a panel of US investor-owned electric utilities from 2001 to 2019. Using the headroom between collateral values and outstanding bonds as a measure of financing capacity, we find a robust inverted-U relationship with adaptation capital, consistent with the model's mechanism. In our preferred specification, adaptation capital peaks at a financing-capacity measure of about 0.48, close to the centre of the observed distribution, with similar turning points across alternative specifications, climate-exposure measures, and sample restrictions. In practical terms, financial headroom appears most valuable for adaptation when it is scarce. Increasing headroom is associated with greater adaptation up to an intermediate level, but beyond that point the relationship reverses.

Much policy debate on adaptation focuses on the volume of available finance. Our results suggest that how adaptation is financed matters as well. Expanding access to finance can support adaptation when financing constraints bind, but financing arrangements must also preserve incentives to undertake future resilience investments. Policies that reduce reliance on costly external equity or mitigate debt-overhang problems may therefore support adaptation not only today, but also as new investment opportunities arise.

More broadly, adaptation is not merely a response to climate risk, but an investment process that unfolds over time and creates new opportunities for resilience. Financing decisions made today can shape whether those opportunities are taken tomorrow. As climate risks intensify and adaptation needs grow, the financing of resilience may become as important as resilience itself.

References

Accetturo, A., Barboni, G., Cascarano, M., Garcia-Appendini, E. and Tomasi, M. (2022). Credit Supply and Green Investments, *SSRN Electronic Journal* .

Acemoglu, D., Akcigit, U., Hanley, D. and Kerr, W. (2016). Transition to Clean Technology, *Journal of Political Economy* **124**: 52–104.

Aghion, P., Bergeaud, A., Ridder, D. and Reenen, V. (2024). Lost in Transition: Financial Barriers to Green Growth, *SSRN Electronic Journal* .

Aghion, P., Dechezleprêtre, A., Hémous, D., Martin, R. and Van Reenen, J. (2016).

Carbon Taxes, Path Dependency, and Directed Technical Change: Evidence from the Auto Industry, *Journal of Political Economy* **124**: 1–51.

Agrawala, S., Bosello, F., Carraro, C., Bruin, K. d., De Cian, E., Dellink, R. and Lanzi, E. (2010). Plan or React? Analysis of Adaptation Costs and Benefits Using Integrated Assessment Models, *OECD Environment Working Papers* **No.23**.

Aivazian, V. A. and Callen, J. L. (1980). Future investment opportunities and the value of the call provision on a bond: Comment, *The Journal of Finance* **35**(4): 1051–1054. **URL:** *https://onlinelibrary.wiley.com/doi/abs/10.1111/j.1540-6261.1980.tb03523.x*

Barrage, L. and Nordhaus, W. (2024). Policies, projections, and the social cost of carbon: Results from the DICE-2023 model, *Proceedings of the National Academy of Sciences of the United States of America* **121**.

Berg, C. N., Bettarelli, L., Davide, F., Ganslmeier, M., Grover, A., Lang, M. E. and Schiffbauer, M. T. (2025). Firm-Level Climate Change Adaptation : Micro Evidence from 134 Nations.

Bettarelli, L., Furceri, D., Ganslmeier, M. and Schiffbauer, M. (2025). *The Economic Costs of Temperature Uncertainty*, International Monetary Fund.

Bilal, A. and Rossi-Hansberg, E. (2023). Anticipating Climate Change Across the United States, *SSRN Electronic Journal* .

Bodie, Z. and Taggart, R. A. (1978). Future Investment Opportunities and the Value of the Call Provision on a Bond, *The Journal of Finance* **33**: 1187–1200.

Bosello, F. (2010). Adaptation, Mitigation and 'Green' R&D to Combat Global Climate Change. Insights from an Empirical Integrated Assessment Exercise, *SSRN Electronic Journal* .

Buchner, B., Naran, B., Fernandes, P., Padmanabhi, R., Rosane, P., Solomon, M., Stout, S., Strinati, C., Tolentino, R., Wakaba, G., Zhu, Y., Meattle, C. and Guzmán, S. (2021). Global Landscape of Climate Finance 2021.

Burke, M., Zahid, M., Martins, M. C., Callahan, C., Lee, R., Avirmed, T., Heft-Neal, S., Kiang, M., Hsiang, S. and Lobell, D. (2024). Are We Adapting to Climate Change?, *NBER Working Paper* **32985**.

Cal. Pub. Util. Code §8386 (2025). Wildfire mitigation plans. https://leginfo.legislature.ca.gov/faces/codes_displaySection.xhtml?lawCode=PUC&sectionNum=8386.

Cal. Pub. Util. Code §8388.5 (2022). Expedited utility distribution infrastructure undergrounding program. Added by Senate Bill 884 (2022). https://leginfo.legislature.ca.gov/faces/codes_displaySection.xhtml?lawCode=PUC&sectionNum=8388.5.

Cevik, S. and Miryugin, F. (2022). Rogue Waves: Climate Change and Firm Performance, *IMF Working Papers* **102**.

CPUC (2024). Resolution SPD-15: Guidelines for the senate bill 884 program. California Public Utilities Commission. Adopted March 7, 2024.

de Bruin, K. C., Dellink, R. B. and Tol, R. S. J. (2009). AD-DICE: an implementation of adaptation in the DICE model, *Climatic Change* **95**: 63–81.

De Haas, R., Martin, R., Muûls, M. and Schweiger, H. (2024). Managerial and Financial Barriers to the Green Transition, *Management science* **71**.

DOE (2016). Climate Change and the Electricity Sector: Guide for Climate Change Resilience Planning.

DOE (2024). Undergrounding transmission and distribution lines: Resilience investment guide, *Technical report*, U.S. Department of Energy, Grid Deployment Office, Washington, DC. Prepared by Lawrence Berkeley National Laboratory.

Duffy, S. (2026). Climate change, adaptation and sovereign risk, *University of Oxford* .

EEI (2012). 2011 Financial Review: Annual Report of the U.S. Shareholder-Owned Electric Utility Industry.

EEI (2020). Rate Case Summary: Q1 2020, Rate of Return.

EEI (2025a). 2024 Financial Review: Annual Report of the U.S. Investor-Owned Electric Utility Industry.

EEI (2025b). Adaptation, Hardening, and Resilience (AHR).

EEI (2026). Finance & accounting.
URL: *https://www.eei.org/en/issues-and-policy/finance-and-tax*

EIB (2023). What drives firms' investment in climate action? Evidence from the 2022-2023 EIB Investment Survey, *European Investment Bank* .

Fazzari, S. M., Hubbard, R. G. and Petersen, B. C. (1988). Financing constraints and corporate investment, *Brookings Papers on Economic Activity* **1988**(1): 141–206.

Felgenhauer, T. and Webster, M. (2013). Multiple adaptation types with mitigation: A framework for policy analysis, *Global Environmental Change* **23**: 1556–1565.

FEMA (2025). Federal Emergency Management Agency (FEMA) National Risk Index Dataset: National Risk Index County_National Risk Index_Rating_Composite - v1.20.

FEMA (2026). Open Federal Emergency Management Agency (FEMA) Dataset: Disaster Declarations Summaries - v2.

Ferrando, A., Groß, J. and Rariga, J. (2023). Climate change and euro area firms' green investment and financing – results from the SAFE.

Guerini, M. and Vona, F. (2025). Can Easing Financial Constraints Reduce Carbon Emissions? Evidence from a Large Sample of French Companies, *FEEM Working Paper* **31**.

Hall, K. (2009). Out of Sight, Out of Mind Revisited An Updated Study on the Undergrounding Of Overhead Power Lines.

Hémous, D. and Olsen, M. (2021). Directed Technical Change in Labor and Environmental Economics, *Annual Review of Economics* **13**: 571–597.

IPCC (2023). Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland., *Climate Change 2023 Synthesis Report* pp. 35–115.

James, J. (2025). U.S. electric utilities: Stability amid uncertainty.

Lanteri, A. and Rampini, A. A. (2025). Financing the Adoption of Clean Technology, *NBER Working Paper* **33545**.

Lazar, J. (2016). *Electricity Regulation in the US: A Guide*, second edn, Regulatory Assistance Project, Montpelier, VT.

Lemoine, D. and Traeger, C. (2014). Watch Your Step: Optimal Policy in a Tipping Climate, *American Economic Journal: Economic Policy* **6**: 137–166.

Lepore, C. and Fernando, R. (2023). Global Economic Impacts of Physical Climate Risks, *IMF Working Paper* .

Mongelli, F. P., Ceglar, A. and Scheid, B. A. (2024). Why Do We Need to Strengthen Climate Adaptations? Scenarios and Financial Lines of Defence, *ECB Working Papers* **3005**.

Myers, S. C. (1977). Determinants of Corporate Borrowing, *Journal of Financial Economics* **5**: 147–175.

Myers, S. C. (1984). The capital structure puzzle, *Journal of Finance* **39**(3): 574–592.

Myers, S. C. and Majluf, N. S. (1984). Corporate financing and investment decisions when firms have information that investors do not have, *Journal of Financial Economics* **13**: 187–221.

NARUC (n.d.). Ferc uniform system of accounts, *Technical report*, National Association of Regulatory Utility Commissioners.
URL: *https://pubs.naruc.org/pub.cfm?id=5381A5A2-2354-D714-5192-728574E7A8E8*

NOAA (2025). National centers for environmental information (ncei) u.s. billion-dollar weather and climate disasters.

OECD (2024). *Climate Adaptation Investment Framework, Green Finance and Investment*, OECD Publishing.

OECD (2025). *Climate Shocks, Debt Defaults and Investment in Climate Adaptation*, OECD Publishing.

Pankratz, N., Bauer, R. and Derwall, J. (2023). Climate Change, Firm Performance, and Investor Surprises, *Management Science* **69**.

PG&E (2025). Quarterly report on form 10-q for the period ended september 30, 2025, PG&E Corporation and Pacific Gas and Electric Company, filed with the SEC.

Phan, T. and Schwartzman, F. (2024). Climate defaults and financial adaptation, *European Economic Review* **170**: 104866.

Ponticelli, J., Xu, Q. and Zeume, S. (2023). Temperature, Adaptation, and Local Industry Concentration, *NBER Working Paper* **31533**.

PPL Electric (2026). Prospectus supplement: 5.75% first mortgage bonds due 2056, PPL Electric Utilities Corporation, Form 424(b)(2), filed with the SEC.

Pörtner, H.-O. and Belling, D. (2022). *Climate Change 2022*, Cambridge University Press.

Rampini, A. A. and Vishwanathan, S. (2013). Collateral and capital structure, *Journal of Financial Economics* **109**: 466–492.

Sautner, Z., Lent, L. V., Vilkov, G. and Zhang, R. (2023). Firm-Level Climate Change Exposure, *The Journal of Finance* **78**.

Schumacher, L. and Hess, W. L. (2010). Regulatory Frameworks – Ratings and Credit Quality for Investor-Owned Utilities: Evaluating a Utility's Regulatory Framework.

Selvans, Z. A., Gosnell, C. M., Sharpe, A., Schira, Z., Lamb, K., Xia, D., Belfer, E. and Mazaitis, K. (2025). Public Utility Data Liberation Project (PUDL) Data Release.

Somanathan, E., Somanathan, R., Sudarshan, A. and Tewari, M. (2021). The Impact of Temperature on Productivity and Labor Supply: Evidence from Indian Manufacturing, *Journal of Political Economy* **129**: 000–000.

Terrell, J. A. (2022). "Fair Value" and "Fair Value to the Obligor": The Mysteries of TIA Section 314(d) Under the Utility Mortgage Bond Indenture, *The National Law Review* .
URL: *https://natlawreview.com/article/fair-value-and-fair-value-to-obligor-mysteries-tia-section-314d-under-utility*

Tex. Util. Code §38.078 (2023). Transmission and distribution system resiliency plan and cost recovery. Added by HB 2555 (2023); implemented by 16 Tex. Admin. Code §25.62.

Van Reenen, J. and Norris Keiller, A. (2024). Disaster Management, *NBER Working Paper* **32595**.

A Appendix

A.1 Data Cleaning and Preparation

This appendix lists the raw FERC, EIA, and FEMA variables used to construct the panel, together with their FERC Uniform System of Accounts (USoA) codes where applicable, and describes the construction of variables used in the empirical analysis. FERC account numbers are taken from the *ferc_account* field in the PUDL datasets and cross-checked against the FERC USoA account listing for public utilities and licensees, hereafter 'the USoA listing' (NARUC, n.d.).

A.1.1 Raw Data Sources

File (origin_data)	Provider / instrument	Schedule (Form 1 page)	Native key	Years pulled	Role in panel
`out_ferc1__yearly_income_statements_sched114`	FERC Form 1 — Statement of Income	Sched. 114–117	`utility_id_pudl` × `report_year`	1996–	Operating income, revenues, interest charges
`out_ferc1__yearly_balance_sheet_assets_sched110`	FERC Form 1 — Balance Sheet, Assets & Other Debits	Sched. 110–113	`utility_id_pudl` × `report_year`	1996–	Total assets, net/gross utility plant, cash, CWIP, accum. depreciation
`out_ferc1__yearly_balance_sheet_liabilities_sched110`	FERC Form 1 — Balance Sheet, Liabilities & Other Credits	Sched. 110–113	`utility_id_pudl` × `report_year`	1996–	Total liabilities, long-term debt, bonds, retained earnings, proprietary capital
`out_ferc1__yearly_plant_in_service_sched204`	FERC Form 1 — Electric Plant in Service (Account 101)	Sched. 204–207	`utility_id_pudl` × `report_year` × `ferc_account`	1996–	Adaptation and overhead capital-stock variables
`out_ferc1__yearly_all_plants`	FERC Form 1	Sched. 402–429	`plant_id_pudl` × `report_year` × `utility_id_pudl`	1996–	Plant → utility → year linkage
`out_eia__yearly_plants`	EIA-860 — Plant file	annual	`plant_id_pudl`, `utility_id_pudl`	all	Plant geography: `latitude`, `longitude`, `county`, `state`, `county_id_fips`

File (origin_data)	Provider / instrument	Schedule (Form 1 page)	Native key	Years pulled	Role in panel
`out_eia__yearly_utilities`	EIA-860 — Utility file	annual	`utility_id_eia` ↔ `utility_id_pudl`	all	EIA–PUDL id bridge; utility name and registration state
`out_eia861__yearly_utility_service_territory`	EIA-861 — Utility Service Territory	annual	`utility_id_eia` × `county_id_fips` × `report_date`	2001–	Service-territory county list and county population
`DisasterDeclarationsSummaries`	FEMA Disaster Declarations Summaries (v2)	—	`disasterNumber` × `designatedArea` (county)	≥1996	County-year counts of major disasters
`NRI_Table_Counties.csv`	FEMA — National Risk Index (2025 county table)	—	`STCOFIPS` (county FIPS)	static	`RISK_SCORE` → `nri_composite_risk`

A.1.2 FERC Form 1 Raw Accounting Variables

Each PUDL "type" label is a row selector within the relevant schedule; the panel pivots these to one column per utility-year. *row_type* = *reported_value* denotes a primary USoA account, while *calculated_value* denotes a FERC Form 1 subtotal.

Balance sheet — Assets (Sched. 110)

Panel column	PUDL `asset_type`	FERC account(s)	USoA / Form 1 line	Row type
`total_assets`	`assets_and_other_debits`	101–283	Total Assets and Other Debits	subtotal
`net_plant_collateral`	`utility_plant_net`	(101–106, 114) − (108, 111, 115); less nuclear fuel net	Net Utility Plant	subtotal
`cash`	`cash`	**131**	Cash	reported

Balance sheet — Liabilities (Sched. 110)

Panel column	PUDL liability_type	FERC account(s)	USoA / Form 1 line	Row type
total_liabilities	liabilities_and_other_credits	201–283	Total Liabilities and Other Credits	subtotal
long_term_debt	long_term_debt	221–226	Total Long-Term Debt	subtotal
bonds	bonds	**221**	Bonds	reported

Statement of Income (Sched. 114)

Panel column	PUDL income_type	FERC account(s)	USoA / Form 1 line	Row type
operating_revenues	operating_revenues	**400**	Utility Operating Revenues (= sum of acct. 440–457)	subtotal
net_utility_operating_income	net_utility_operating_income	400 minus operating expenses (401–407, 408.1, 409.1, 410.1, 411.1, 411.4, 412–413)	Net Utility Operating Income	subtotal
net_interest_charges	net_interest_charges	427–431 minus 432	Net Interest Charges	subtotal

Electric Plant in Service (Sched. 204) — capital-stock building blocks

Values are ending_balance for gross plant in service and all relevant rows are in service, aggregated to the utility-year level by FERC account.

ferc_account_label	FERC acct.	USoA name
Underground → stock_adaptation		
underground_conduit_transmission_plant	**357**	Underground conduit (transmission)
underground_conductors_and_devices_transmission_plant	**358**	Underground conductors and devices (transmission)
underground_conduit_distribution_plant	**366**	Underground conduit (distribution)
underground_conductors_and_devices_distribution_plant	**367**	Underground conductors and devices (distribution)
Energy storage → stock_energy_storage		
energy_storage_equipment_transmission_plant	**351**	Energy Storage Equipment (transmission)

ferc_account_label	FERC acct.	USoA name
energy_storage_equipment_distribution_plant	**363**	Energy Storage Equipment (distribution)
Overhead → stock_overhead		
towers_and_fixtures_transmission_plant	**354**	Towers and fixtures (transmission)
poles_and_fixtures_transmission_plant	**355**	Poles and fixtures (transmission)
overhead_conductors_and_devices_transmission_plant	**356**	Overhead conductors and devices (transmission)
poles_towers_and_fixtures_distribution_plant	**364**	Poles, towers and fixtures (distribution)
overhead_conductors_and_devices_distribution_plant	**365**	Overhead conductors and devices (distribution)

A.1.3 Non-FERC Raw Inputs

FEMA disaster declarations → county-year shock counts

From official file `DisasterDeclarationsSummaries`:

- `report_year` is the calendar year of `incidentBeginDate`.
- County FIPS is constructed from `fipsStateCode` and `fipsCountyCode`.

We retain declarations classified as Drought, Flood, Freezing, Severe Storm, Severe Ice Storm, Tropical Storm, Typhoon, Hurricane, Fire, Winter Storm, Tornado, Coastal Storm, Earthquake, Snowstorm, Tsunami, or Volcanic Eruption. The total shock at county-level in year t is defined as:

$$\text{shock_count}_{c,t} = \#\{\text{qualifying declarations in county } c \text{ beginning in year } t\}.$$

FEMA National Risk Index → county risk

From `NRI_Table_Counties.csv`, $\texttt{nri_composite_risk}_c$ is the `RISK_SCORE` for county `STCOFIPS`. The county-level measure is time invariant.

EIA-861 service territory → utility state

For each utility-year, `utility_state` is the state containing the largest share of the utility's service-territory population. Missing values are filled within utilities where possible. Utilities absent from EIA-861 are assigned their EIA-860 registration state.

A.1.4 Constructed Variables

Throughout, i indexes utilities and t years. Dollar aggregates are treated as missing when all underlying components are missing.

Capital stocks

$$\begin{aligned}
\text{stock_adaptation}_{it} &= \sum(\text{acct } 357, 358, 366, 367), \\
\text{stock_energy_storage}_{it} &= \sum(\text{acct } 351, 363), \\
\text{stock_overhead}_{it} &= \sum(\text{acct } 354, 355, 356, 364, 365), \\
\textbf{adaptation_stock}_{it} &= \text{stock_adaptation}_{it} + \text{stock_energy_storage}_{it}, \\
\textbf{total_td_stock}_{it} &= \text{stock_overhead}_{it} + \text{adaptation_stock}_{it}.
\end{aligned}$$

Annual capital additions in Figure 6

Let

$$\Delta^{\text{ad}}_{it} = \text{adaptation_stock}_{it} - \text{adaptation_stock}_{i,t-1}$$

denote the year-on-year change in adaptation capital, and let Δ^{oh}_{it} denote the analogous change in overhead capital. The series shown in Figure 6 are

$$\begin{aligned}
\text{adaptation investment}_{it} &= \max(\Delta^{\text{ad}}_{it}, 0), \\
\text{overhead investment}_{it} &= \max(\Delta^{\text{oh}}_{it}, 0).
\end{aligned}$$

Financial variables

Variable	Definition
`log_assets`	$\ln(\text{total_assets}_{it})$
`log_operating_revenues`	$\ln(\text{operating_revenues}_{it})$
`leverage_long_term`	$\text{long_term_debt}_{it}/\text{total_assets}_{it}$
`cash_ratio`	$\text{cash}_{it}/\text{total_assets}_{it}$
`financing_capacity`	$\dfrac{\text{net_plant_collateral}_{it} - \text{bonds}_{it}}{\text{total_assets}_{it}}$
`interest_coverage`	$\dfrac{\text{net_utility_operating_income}_{it}}{\text{net_interest_charges}_{it}}$; defined for positive interest charges and capped at 15 before winsorisation

Real variables

Nominal values are converted to constant 2019 dollars using the annual BLS CPI-U, All

Items, U.S. city average (series `CUUR0000SA0`), with

$$d_t = \frac{\text{CPI}_{2019}}{\text{CPI}_t}.$$

Total assets and operating revenues are deflated by using their contemporaneous price level. For adaptation and overhead capital stocks, which contain investments made in different years, we construct vintage-consistent real stocks. Within each uninterrupted reporting spell,

$$K^{\text{real}}_{i,t_0} = K^{\text{nom}}_{i,t_0} d_{t_0}, \qquad I^{\text{real}}_{it} = \left(K^{\text{nom}}_{it} - K^{\text{nom}}_{i,t-1}\right) d_t,$$
$$K^{\text{real}}_{it} = K^{\text{real}}_{i,t-1} + I^{\text{real}}_{it}.$$

K^{nom}_{it} is positive. The reported FERC year-end balances incorporate asset retirements, so changes in nominal balances are net of retirements. The main dependent variable used in the empirical section is $ln(K^{real}_{it})$.

Five-year moving averages

Except for the adaptation capital stock, time-varying variables enter the empirical analysis as backward averages over the preceding five calendar years:

$$\bar{x}^{(5)}_{it} = \frac{1}{n_{it}} \sum_{k=1}^{5} x_{i,t-k}, \qquad n_{it} \geq 4,$$

where n_{it} is the number of non-missing observations in the five-year window. Our core inverted-U relationship in Table 4 remains robust if set $n = 5$.

Climate exposure

Climate exposure is constructed over two geographic footprints:

- *Territory*: counties in utility i's EIA-861 service territory.
- *Plant*: counties containing utility i's FERC-reporting generation plants.
- *Combined*: the union of the territory and plant counties.

Variable	Definition
`territory_shock_count`$_{it}$	$\sum_{c \in \text{territory}(i,t)} \text{shock_count}_{c,t}$
`combined_shock_count`$_{it}$	$\sum_{c \in \text{territory}(i,t) \cup \text{plant}(i,t)} \text{shock_count}_{c,t}$
`territory_nri_composite_risk`$_{it}$	Mean `nri_composite_risk`$_c$ across territory counties; the combined measure is defined analogously
`territory_nri_high` / `combined_nri_high`	Indicator equal to one when the corresponding average NRI score lies in the top quartile of its sample distribution

Sample construction

We merge the financial, plant-in-service, and climate data at the utility-year level. We exclude entities that are not investor-owned electric utilities, including cooperatives, ISOs/RTOs, generation- or transmission-only subsidiaries, non-operating holding companies, and municipal or water utilities. We then exclude utilities that never report positive bond financing, restrict the sample to 2001–2019, remove utilities that never report a positive adaptation capital stock during the estimation period, and require at least three sample years per utility. Annual flows and ratios are winsorised at the 1st and 99th percentiles before constructing the five-year backward moving averages. The resulting panel contains 2,331 utility-years for 132 utilities, as described in Section 4.3.

A.2 Comparison of the Full Panel and Estimation Sample

As discussed in Section 4.3, the preferred specification restricts the full panel of 2,331 utility-years to 1,424 complete observations. This appendix examines whether that restriction materially changes the composition of the sample. Table 13 compares the distributions of the regression variables across the full and estimation samples.

	Full sample				Estimation sample		
Variable	N	**Mean (SD)**	**Median**	**% miss**	N	**Mean (SD)**	**Median**
Log adaptation stock	2331	19.617 (1.656)	19.676	0.0	1424	19.779 (1.666)	19.872
Financing capacity (MA-5)	1882	0.450 (0.141)	0.448	19.3	1424	0.453 (0.132)	0.449
Financing capacity^2 (MA-5)	1882	0.222 (0.128)	0.200	19.3	1424	0.223 (0.121)	0.202
Combined shock count (MA-5)	2015	12.494 (15.019)	6.200	13.6	1424	11.691 (14.779)	5.600
Combined NRI high (MA-5)	2000	0.237 (0.416)	0.000	14.2	1424	0.232 (0.411)	0.000
Log real assets (MA-5)	2285	22.094 (1.361)	22.208	2.0	1424	22.191 (1.433)	22.264
Cash ratio (MA-5)	1930	0.002 (0.003)	0.002	17.2	1424	0.002 (0.003)	0.002
Log real operating revenues (MA-5)	2288	21.794 (1.278)	21.902	1.8	1424	21.869 (1.361)	21.965
Interest coverage (MA-5)	2281	2.737 (1.019)	2.602	2.1	1424	2.681 (0.827)	2.605
Long-term leverage (MA-5)	2274	0.284 (0.071)	0.287	2.4	1424	0.292 (0.067)	0.293

Full sample = master panel of utilities with spell ≥ 3 years, $N = 2331$ utility-years. Estimation sample = complete cases on the full-sample year + state FE stock specification, $N = 1424$ utility-years.

Table 13: Variable distributions: full panel vs. stock-regression estimation sample (year + state FE, quadratic financing capacity)

Financing capacity is distributed very similarly across the full and estimation samples. The estimation sample contains somewhat larger utilities and a slightly higher average adaptation capital stock. Overall, the sample restriction does not appear to select observations systematically on the financing-capacity measure central to the analysis. Figure 8 provides the corresponding distributional comparison.

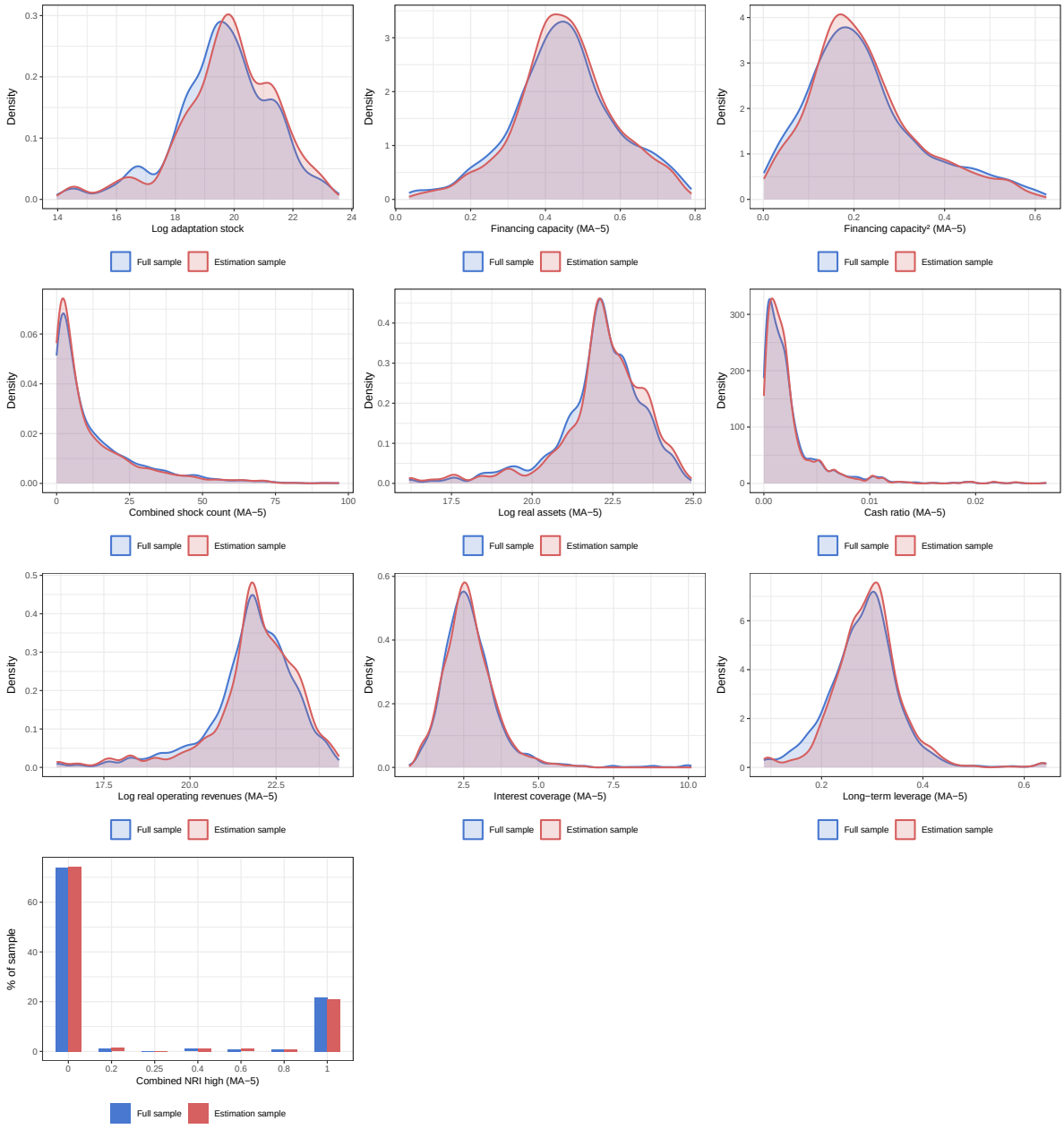


Figure 8: Variable Distributions: Full Panel and Estimation Sample