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ORIGINAL ARTICLE

Regulatory Uncertainty: Asset Allocation and Asset Pricing

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Abstract Regulatory uncertainty is a central channel through which policy affects financial decisions. We develop a programmatic conceptual framework for studying regulatory uncertainty in asset allocation and asset pricing. We define regulatory uncertainty as uncertainty about the design, timing, implementation, interpretation, and enforcement of regulations that directly shape cash flows, feasible actions, institutional constraints, and market expectations. This perspective distinguishes regulatory uncertainty from broader economic policy uncertainty by focusing on regulations, regulatory parameters, and enforcement practices rather than on policy uncertainty in general. The framework identifies four main entry points into financial models: cash-flow dynamics, beliefs and learning, regulatory constraints including tax constraints,

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and intermediary capital and liquidity constraints. It also clarifies when regulatory uncertainty is merely reflected in expected cash flows and when it commands a risk premium. We illustrate the framework in selected domains in which regulatory uncertainty is economically important: financial regulation, climate policy, taxation, and insurance. We thereby provide a common language for connecting theoretical modeling, measurement, and empirical analysis of regulatory uncertainty and for deriving implications for investors, firms, intermediaries, and regulators.

Keywords Regulatory Uncertainty · Asset Allocation · Asset Pricing · Financial Regulation · Climate Policy · Tax Uncertainty

JEL Classification G 11 · G 12 · G 18 · H 21 · H 32 · Q 54

1 Introduction

Regulation is a defining feature of modern financial markets and institutions. Capital requirements, risk-based solvency regulations, climate transition policies, and tax systems all shape investment opportunities, constraints, and expectations across a wide range of economic activities. In practice, however, market participants rarely operate in a fixed and fully known regulatory environment. Instead, regulatory frameworks evolve, political priorities shift, and both timing and content of regulatory interventions are often uncertain. This regulatory uncertainty is a specific form of economic policy uncertainty with important implications for firms' asset-allocation and financing decisions as well as for asset prices.

We use uncertainty as an umbrella term for incomplete knowledge about future regulatory states and their economic consequences, including the timing, design, content, interpretation, and enforcement of regulations. The appropriate formal representation depends on the information available to market participants. When the relevant regulatory states and their probabilities are specified, regulatory uncertainty can be modeled as stochastic risk, for example through regime-switching processes. When participants do not directly observe the prevailing regime or its economic effects but update their beliefs in response to regulatory signals, announcements, or observed policy actions, regulatory uncertainty takes the form of a learning problem. In settings in which no unique probability distribution or model can be assigned to future regulatory states, it may instead be represented as ambiguity or model uncertainty. Ambiguity is therefore one particular representation of regulatory uncertainty rather than a synonym for it. In empirical applications, these different information structures can be studied using survey-based measures, text-based indicators, market-implied quantities, event studies, or regulatory data. Depending on the underlying representation and transmission mechanism, regulatory uncertainty may affect asset allocation and asset prices through expected cash flows, feasible choice sets, discount rates, hedging demand, belief updating, risk premia, or, in models with ambiguity, ambiguity premia.

Prominent examples illustrate the economic relevance of regulatory uncertainty across policy domains: Trade policy conflicts and tariff wars create sudden changes

in import tariffs, export controls, and trade agreements, affecting global value chains, cash flows, and firms' cost of capital. Climate policy uncertainty arises when expectations about the stringency, timing, or scope of carbon pricing schemes, green subsidy programs, disclosure requirements, or transition pathways remain unclear or shift over time. Uncertainty about corporate and personal taxation, including major tax reforms reflecting international coordination of anti-tax-avoidance regulations, domestic tax incentives, and tax enforcement, adds an additional layer of regulatory uncertainty that can distort investment, financing, and location choices.

While the existing literature has established the importance of economic policy uncertainty for asset allocation and asset prices, it has largely treated regulation as part of a broader and rather undifferentiated policy environment. Regulatory uncertainty, by contrast, arises from uncertainty about the regulations that directly govern permissible actions, risks, and payoffs, and therefore warrants separate conceptual attention. The German Research Foundation (Deutsche Forschungsgemeinschaft, DFG) Research Unit 5583 (FOR 5583), "Asset Allocation and Asset Pricing under Regulatory Uncertainty," takes regulatory uncertainty as its central organizing concept. It studies how uncertainty about regulations, regulatory parameters, and enforcement affects optimal asset allocation, the pricing of risks in financial markets, and investment behavior in regulated environments. In addition to sector-specific financial regulation, the research program explicitly accounts for interactions between prudential regulations and broader regulatory domains such as trade, climate, and taxation. For example, tariff wars and other trade policy shocks can alter the effectiveness and incidence of capital and liquidity regulations, climate transition policies can reshape stranded-asset risks and hedging demands, and tax reforms can change after-tax returns, portfolio composition, and the incentives to use regulatory arbitrage. By modeling these interactions, FOR 5583 helps to better understand when and how regulatory uncertainty is reflected in asset prices, how it propagates across sectors, and which forms of regulatory arbitrage may emerge endogenously.

This agenda can draw on the broader literature on uncertainty and economic policy uncertainty, especially for empirical measurement and evidence on how policy-related uncertainty affects expectations, investment, financing, and asset prices. These contributions provide useful starting points, but they typically measure policy uncertainty at a broader level than the regulatory mechanisms emphasized here. For surveys, measures, and applications, see, for example, Pástor and Veronesi (2012, 2013); Brogaard and Detzel (2015); Baker et al. (2016); Hassan et al. (2019); Altig et al. (2020); French and Li (2022); Bossman et al. (2023).

Building on this empirical and measurement-oriented literature, the research program also draws on foundational work in dynamic portfolio choice and asset pricing under risk and rare events (Merton 1969, 1971; Rietz 1988; Bansal and Yaron 2004; Barro 2009; Branger et al. 2016; Chen et al. 2018a), extends models with ambiguity and learning (Ellsberg 1961; Hansen and Sargent 2001; Klibanoff et al. 2005; Garlappi et al. 2007; Chen et al. 2019; Balter et al. 2021; Bäuerle and Mahayni 2024), and explicitly incorporates regulatory constraints and policy uncertainty (Basak and Shapiro 2001; Pástor and Veronesi 2012, 2013; Davis 2017; Chen et al. 2018b; Hassan et al. 2019; Bäuerle and Chen 2023; Koziol and Kuhn 2023). Against this background, considering interactions between different regulatory and policy do-

mains, such as financial regulation, trade policy, climate policy, and taxation, provides a natural way to study regulatory uncertainty in settings where it arises across sectors and markets.

The need for such a framework arises because regulatory uncertainty is a cross-cutting topic that appears in several fields, including finance, insurance, taxation, climate economics, econometrics, and political economy. These fields often study related phenomena but use different terminology and emphasize different mechanisms. As a result, insights about regulatory uncertainty remain fragmented across domains. We therefore develop a framework for organizing research on regulatory uncertainty in asset allocation and asset pricing and illustrate how the framework can guide theoretical and empirical work across regulated domains.

With this article we make three contributions. First, we distinguish regulatory uncertainty from broader economic policy uncertainty by focusing on uncertainty about regulations, regulatory parameters, enforcement, and institutional constraints. Second, we link this concept to asset allocation and asset pricing by identifying the model objects through which regulatory uncertainty enters decision problems: cash-flow dynamics, beliefs and learning, feasible choice sets, and intermediary capital, liquidity, leverage, and profitability constraints. Third, we show how the framework can guide modeling, measurement, and empirical analysis in sector-specific regulation, climate regulation, and taxation, including spillovers across regulatory domains. We thus provide a generalizable framework while using the projects of FOR 5583 as illustrations of how the framework can be operationalized.

The remainder is organized as follows. Section 2 develops the conceptual distinction between regulatory uncertainty and related forms of uncertainty and introduces the framework linking sources, channels, measures, and outcomes. Section 3 discusses selected application domains in which regulatory uncertainty is particularly relevant. Section 4 uses selected projects to illustrate methodological implementations in modeling, measurement, and empirical analysis. Section 5 concludes by summarizing the framework and outlining implications for future research.

2 Regulatory Uncertainty as a Form of Economic Policy Uncertainty

Regulatory uncertainty is related to, but distinct from, legal uncertainty, political uncertainty, and broad economic policy uncertainty. Legal uncertainty concerns uncertainty about the interpretation or enforceability of legal provisions. Political uncertainty concerns uncertainty about political actors, electoral outcomes, legislative bargaining, or policy priorities. Economic policy uncertainty is broader and captures uncertainty about government action and the macroeconomic policy environment. Regulatory uncertainty overlaps with these concepts, but it is narrower in its object: it concerns uncertainty about regulations, regulatory parameters, and enforcement practices that directly constrain or guide economic actions and financial payoffs. Thus, political uncertainty may become regulatory uncertainty when it changes expectations about capital requirements, carbon-pricing regulations, disclosure mandates, tax bases and rates, or enforcement intensity. Legal uncertainty may become

Table 1 Dimensions of regulatory uncertainty

Dimension	Object of uncertainty	Main economic relevance	Examples
Future regulatory interventions	Timing, likelihood, and design of new regulations	Affects expectations, option values, investment timing, and hedging demand	New capital requirements, climate policies, tax reforms
Regulatory parameters and scope	Numerical thresholds, regulatory parameters, and the set of affected firms, assets, or transactions	Changes feasible actions, after-tax payoffs, binding constraints, and incentives for regulatory arbitrage	VaR or ES levels, solvency thresholds, tax rates, loss-offset rules, emission limits
Interpretation and enforcement	Supervisory interpretation, audit intensity, penalties, administrative guidance, and court decisions	Affects compliance costs, expected payoffs, perceived constraints, and location or reporting choices	Tax enforcement, supervisory practice, disclosure interpretation, litigation risk
Cross-domain interactions	Interactions between financial regulation, taxation, climate policy, trade policy, and other regulatory domains	Creates spillovers across sectors, firms, intermediaries, and asset classes	Climate-related capital effects, tax-induced portfolio shifts, trade-policy shocks to regulated firms

regulatory uncertainty when an ambiguous interpretation changes compliance costs, feasible actions, or after-tax payoffs.

These relationships can also run in the opposite direction. Regulatory uncertainty may generate political uncertainty when anticipated or contested regulatory changes affect electoral competition, lobbying, coalition stability, or government credibility. It may generate legal uncertainty when unclear or changing regulations give rise to disputes over statutory authority, interpretation, or enforceability. The concepts should therefore be viewed as overlapping and potentially mutually reinforcing rather than as linked by a one-way mapping.

Empirically, the distinction from general economic policy uncertainty can be implemented by measuring whether an uncertainty signal refers to a regulation that changes permissible actions, payoffs, compliance costs, enforcement probabilities, or regulatory constraints. Broad economic policy uncertainty measures remain useful controls, but the regulatory component is identified by the institutional object of regulatory uncertainty such as capital regulations, solvency thresholds, disclosure mandates, carbon-pricing regulations, tax bases and rates, loss-offset provisions, audit probabilities, or related enforcement practices. Thus, the proposed approach is complementary to existing economic policy uncertainty measures. It aims to isolate the part of policy uncertainty that enters financial decisions through explicit regulations and constraints.

Table 1 summarizes the dimensions of regulatory uncertainty that are central to our framework. The table does not provide an exhaustive classification of all forms of policy uncertainty. Instead, it identifies the types of uncertainty that are most relevant for asset allocation and asset pricing because they affect payoffs, feasible actions, beliefs, or constraints. Building on these dimensions, regulatory uncertainty can enter asset allocation and asset pricing models through several model objects: the data-generating processes of returns and cash flows, investors' and intermediaries'

Table 2 Positioning relative to related research strands

Research strand	Main focus and limitation for our purpose	Representative literature
Economic policy uncertainty	This literature studies broad uncertainty about government policy, macroeconomic policy, and political decisions. For our purpose, however, regulatory constraints, enforcement, and institutional parameters need to be separated more explicitly from broader policy uncertainty	Pástor and Veronesi (2012, 2013); Baker et al. (2016); Hassan et al. (2019) Altig et al. (2020); French and Li (2022); Bossman et al. (2023)
Dynamic portfolio choice and asset pricing under risk	This literature provides the foundations for optimal investment and asset pricing with stochastic investment opportunities, rare events, and changing risks. Regulatory uncertainty, however, is usually not modeled as an explicit source of changing constraints or institutional regimes	Merton (1969, 1971); Rietz (1988); Bansal and Yaron (2004) Barro (2009); Branger et al. (2016); Chen et al. (2018a)
Ambiguity, robust decision making, and learning	This literature studies model uncertainty, learning about unknown parameters, and decisions under ambiguity. It is central to our approach, but institutional and regulatory constraints are often treated as fixed, exogenous, or only indirectly represented	Ellsberg (1961); Hansen and Sargent (2001); Klibanoff et al. (2005) Garlappi et al. (2007); Chen et al. (2019); Balter et al. (2021); Bäuerle and Mahayni (2024)
Regulatory constraints in finance	This literature studies how capital, solvency, risk, and portfolio constraints affect financial decisions and prices. The regulations themselves, however, are often fixed rather than uncertain in timing, scope, interpretation, or enforcement	Basak and Shapiro (2001); Sialm (2006); Chen et al. (2018b); Davis (2017) Bäuerle and Chen (2023); Koziol and Kuhn (2023)
Taxation, regulatory uncertainty and decision-making	This literature studies tax policy, tax enforcement, tax complexity, and tax uncertainty, and how regulatory uncertainty translates into firm-level decisions. The link to asset allocation, asset pricing, and cross-domain regulatory interactions is often not the primary focus	Edmiston (2004); Niemann (2011); Devereux (2016); Guceri and Albinowski (2021); Fox et al. (2022); Jacob et al. (2022); Hoppe et al. (2023); Osswald and Sureth-Sloane (2024); Gallemore et al. (2025)
Climate policy and transition regulation	This literature studies climate policy, transition risks, disclosure requirements, regulatory pathways, and portfolio constraints based on carbon-risk measures. Our framework emphasizes the distinction between expected policy direction, measured carbon-risk exposures, and uncertainty about the timing, scope, and enforcement of climate-related regulation	Fuss et al. (2008), NGFS Network for Greening the Financial System; Barnett et al. (2020); Bolton and Kacperczyk (2023); Chen et al. (2025a)

beliefs, feasible choice sets, and regulatory or institutional constraints. These entry points provide a link between the conceptual definition of regulatory uncertainty and the model-based and empirical applications discussed below.

From an asset-pricing perspective, it is useful to distinguish between regulatory uncertainty that merely affects expected payoffs and regulatory uncertainty that is priced as a systematic source of risk or ambiguity. Regulatory uncertainty is reflected in asset prices whenever it affects expected cash flows, constraints, or discount rates. It commands a premium only under stronger conditions: when regulatory shocks covary with marginal utility, affect aggregate investment opportunities or intermediary capital and liquidity capacity, tighten constraints in bad states of the world, or cannot be diversified away because they operate at the sectoral or economy-

wide level. This distinction is central to linking regulatory uncertainty to risk premia, ambiguity premia, and cross-sectional asset-pricing effects.

Table 2 positions our framework relative to related strands of the literature. The references are representative rather than exhaustive and indicate the main research traditions on which the framework builds. Since many contributions speak to several mechanisms at once, the table groups the literature by broader research strands rather than assigning individual studies to isolated channels. The contribution of our framework is to connect these strands through the common concept of regulatory uncertainty and to link them to asset allocation and asset pricing.

This positioning also clarifies the role of FOR 5583 within the existing literature. The research unit builds on work on economic policy uncertainty, dynamic portfolio choice, asset pricing under risk and rare events, ambiguity, learning, regulatory constraints, taxation, and climate policy. Its distinctive focus is to study regulatory uncertainty not merely as an external exposure measure, but as a feature of the economic environment that directly affects payoff dynamics, beliefs, feasible choice sets, and regulatory or institutional constraints.

This perspective is particularly useful in domains in which regulations directly shape financial payoffs, constraints, and investment opportunities. In the following we therefore focus on three selected application areas: sector-specific regulation, climate regulation, and taxation. Sector-specific regulation is central because capital, solvency, liquidity, disclosure, risk management, and other industry-specific requirements directly affect asset allocation and asset pricing in regulated sectors. Climate regulation is important because transition policies affect relative cash flows, long-horizon risks, disclosure requirements, and hedging demand. Taxation is relevant because tax regulations affect after-tax returns, financing choices, payout policy, and investment incentives. These domains are not exhaustive, but they illustrate how the same conceptual framework can be applied across different regulatory environments.

Methodologically, the framework motivates models in which regulatory uncertainty is represented through ambiguity about the data-generating process, learning about future regulatory regimes, or uncertainty about future constraints and enforcement. These approaches build on frameworks of model ambiguity, robust decision making, and learning (Ellsberg 1961; Hansen and Sargent 2001; Klibanoff et al. 2005; Bäuerle and Rieder 2007, 2020; Garlappi et al. 2007; Fernholz and Karatzas 2011; Bäuerle and Mahayni 2024; Chen et al. 2025c). On the empirical side, the framework connects to approaches that measure uncertainty using surveys, textual analysis, regulatory data, and market-based information (Devereux 2016; Gentzkow et al. 2019; Hassan et al. 2019, NGFS Network for Greening the Financial System; Guceri and Albinowski 2021; Hoppe et al. 2023; Gallemore et al. 2025). Together, these perspectives make it possible to translate regulatory uncertainty into model objects and empirical measures that can be linked to returns, investment, and regulatory arbitrage behavior.

3 Regulatory Uncertainty in Selected Application Areas

The application areas discussed in this section are illustrative and are neither mutually exclusive nor exhaustive. They were selected because regulatory uncertainty is economically important in each of them and because they correspond to complementary expertise within the research unit. The common framework developed above allows us to analyze these domains in a unified way: in each case, uncertainty about regulations affects payoffs, beliefs, feasible actions, or constraints, and thereby creates implications for asset allocation and asset pricing. We focus, first, on sector-specific regulation, with financial regulation as a central example, because capital, solvency, liquidity, disclosure, and risk-management requirements directly affect asset-allocation decisions and asset prices in regulated sectors. Second, we focus on climate regulation because transition policy changes relative cash flows, long-horizon risks, disclosure requirements, and hedging demand. Third, we focus on taxation because tax regulations affect after-tax returns, financing choices, payout policy, and investment incentives. The same logic can be extended to further domains, such as competition policy, data regulation, or health regulation.

Across these domains, regulatory uncertainty is heterogeneous in its institutional sources but similar in its economic logic. It arises from uncertainty about the timing, design, calibration, interpretation, or enforcement of regulations and becomes relevant for asset allocation and asset pricing through its effects on cash flows, constraints, beliefs, and risk premia. In empirical applications, regulatory uncertainty may therefore be measured separately by domain, jointly through composite indicators, or through interaction terms that capture overlap across domains. Domain-specific measures help identify the direct contribution of a particular regulatory area, whereas joint and interaction measures help analyze how uncertainty propagates across regulatory boundaries, for example through climate stress testing, carbon border adjustment mechanisms, or cross-border tax rules.

Sector-specific Regulation Sector-specific regulation covers regulatory environments in which firms or intermediaries face industry-specific rules, supervisory requirements, or institutional constraints. Financial institutions such as banks and insurers are a central example. They operate under extensive prudential regulation, including capital requirements, solvency rules, liquidity requirements, and risk-management frameworks such as Basel III and Solvency II. These regulations are often formalized as constraints in optimal portfolio, balance-sheet, and risk-management problems. Regulatory uncertainty arises when the design, calibration, interpretation, or enforcement of these regulations is subject to change, for example through changes in Value-at-Risk or Expected Shortfall thresholds, the design of stress tests, or the introduction of new guarantee, recovery, or resolution requirements.

Such uncertainty rarely operates in isolation. Sector-specific regulation can interact with broader policy developments, including trade policy, climate policy, and taxation. Trade-policy uncertainty, tariff changes, or trade disputes may affect sectoral exposures, funding conditions, and macroeconomic risks, thereby changing the environment in which prudential regulation operates. In some cases, these develop-

ments change the effective tightness and binding probability of capital, solvency, or liquidity constraints; in others, they primarily affect cash-flow dynamics, asset returns, and equilibrium risk premia. These interactions motivate research questions on how intermediaries adjust portfolios when market risks and regulatory conditions are jointly uncertain, and on how such adjustments affect asset prices and incentives for regulatory arbitrage. For regulatory constraints and their asset-pricing implications, see Basak and Shapiro (2001); Chen et al. (2018b, 2019); Kara and Ozsoy (2020); Bäuerle and Chen (2023); Branger et al. (2023); Koziol and Kuhn (2023). On systemic risk and networks in the financial sector, see Benoit et al. (2017); Hautsch et al. (2015). Related dynamic portfolio-choice frameworks with learning and partial information include Karatzas and Zhao (2001); Xia (2001); Cvitanic et al. (2006); Kan and Zhou (2007); Björk et al. (2010); Bäuerle and Chen (2019); Bäuerle and Mahayni (2024).

Climate Regulation The transition to a low-carbon economy is shaped by climate-policy instruments such as carbon taxes, emissions trading schemes, disclosure requirements, green subsidies, climate stress tests, and sector-specific transition regulations. While a growing literature studies the implications of climate risk for asset allocation and asset prices (Fuss et al. 2008; Barnett et al. 2020; Bolton and Kacperczyk 2023; Chen et al. 2025a), climate policy frameworks are often treated as fixed or exogenously given. Our framework instead emphasizes uncertainty about future carbon prices, emissions caps, disclosure requirements, transition pathways, and the regulatory treatment of carbon-intensive and low-carbon assets. This uncertainty affects the relative valuation of brown and green assets, long-horizon risk premia, and hedging demand.

Climate regulation also illustrates how regulatory uncertainty propagates across domains. Climate stress testing links climate policy to financial regulation; carbon border adjustment mechanisms link climate policy to trade policy; and green subsidies or tax incentives link climate policy to taxation. These interactions can change portfolio allocations, sectoral exposures, and incentives to relocate investment across assets and jurisdictions. This line of work connects to early contributions on climate policy and investment (Nordhaus 1992b; Blyth et al. 2007; Seifert et al. 2008; Szolgayova et al. 2008; Linnerud et al. 2014; Boomsma and Linnerud 2015), to broader work on climate finance, climate risk, and climate policies (IEA International Energy Agency; Battiston et al. 2017, NGFS Network for Greening the Financial System; Engle et al. 2020; Krueger et al. 2020; Ilhan et al. 2021; Giglio et al. 2021; Barnett 2023; Sautner et al. 2023; Acharya et al. 2023), and to research on climate risk and long-run growth (Bansal and Yaron 2004; Bansal et al. 2016, 2019; Rudebusch 2019). It also relates to work on macro shocks (Gormsen and Koijen 2020) and on macroeconomic and political uncertainty (Hassan et al. 2019; Coibion et al. 2022).

Taxation Tax systems play a central role in both corporate and investor decisions. They are characterized by substantial regulatory uncertainty arising from legislative changes, administrative practices, judicial decisions, enforcement intensity, and interactions between domestic and international tax rules. Unlike approaches that rely on fixed or purely stochastic tax rates without taking institutional structure

into account, our framework treats tax uncertainty as multidimensional. It includes uncertainty about statutory tax rates, tax bases, the treatment of losses, enforcement probabilities, audit intensity, and the availability or design of instruments that mitigate exposure to specific forms of tax uncertainty.

Tax-related regulatory uncertainty affects asset allocation and asset pricing through several channels. It changes after-tax returns and discount rates. It can also alter financing choices, payout policy, and investment incentives. Taxation further interacts with other policy domains. Financial regulation and taxation jointly shape leverage and financing decisions. Climate policy and taxation interact through carbon taxes, green investment incentives, and the tax treatment of transition-related expenditures. Trade policy and taxation interact through cross-border rules and the location of taxable income. These links make tax-related regulatory uncertainty an integral part of the broader regulatory environment that shapes investment behavior, portfolio composition, and asset prices. For studies on how tax uncertainty and tax rules affect asset allocation, asset pricing, and real investment, see Sialm (2006, 2009); Dai et al. (2008); Seifried (2010); Niemann (2011); Fleckenstein et al. (2019); Guceri and Albinowski (2021); Jacob et al. (2022); Osswald and Sureth-Sloane (2024); Chen et al. (2025b).

Across these application areas, the research program organizes its contributions along three methodological layers.

- *Modeling.* Regulatory uncertainty is incorporated into continuous- and discrete-time asset allocation and asset pricing frameworks, allowing for ambiguity, learning, and regime switching (Merton 1969, 1971; Hansen and Sargent 2001; Klibanoff et al. 2005; Bäuerle and Rieder 2007, 2020; Garlappi et al. 2007; Guidolin and Timmermann 2007; Liu 2011; Ang and Timmermann 2012; Capponi and Figueroa-López 2014; Bo et al. 2019; Bäuerle and Mahayni 2024).
- *Measurement.* Regulatory uncertainty is measured using high-dimensional data, textual analysis, regulatory information, and market-implied quantities (Jurado et al. 2015; Baker et al. 2016; Gentzkow et al. 2019; Hassan et al. 2019, NGFS Network for Greening the Financial System; Altig et al. 2020; Eberbach et al. 2021; Chen et al. 2025b).
- *Implications.* The implications of regulatory uncertainty for optimal portfolios, equilibrium asset prices, firm-level investment, financing decisions, and regulatory arbitrage are examined across regulated environments (Acemoglu et al. 2012; Pástor and Veronesi 2012, 2013; Carvalho 2014; Brogaard and Detzel 2015; Hautsch et al. 2015; Herskovic 2018; Gofman et al. 2020; Branger et al. 2021; Jacob et al. 2022; Gallemore et al. 2025).

A common feature across application areas is that these layers are explicitly linked. Measurement informs the state variables and uncertainty processes entering the models; the models generate testable implications for prices, portfolios, and real decisions; and the empirical analyses identify the channels through which regulatory uncertainty affects observed outcomes. The following section provides a deeper discussion of selected projects of the research unit that span these methodological layers and application areas.

Table 3 Project-specific methodological implementation

Project area	Methodological approach	Main regulatory object	Expected output
Financial decisions	Continuous-time portfolio choice with ambiguity, learning, and regulatory constraints	Uncertain asset dynamics, VaR/ES thresholds, solvency constraints, tax regulation	Portfolio demand, welfare costs, certainty equivalents, shadow costs, optimal fee for regulatory certainty
Networks	Dynamic network estimation and network-aware identification	Direct and indirect exposure to regulatory shocks or regulatory uncertainty	Spillover measures, network risk premia, treatment effects under interference
Regime switches	Hidden Markov and regime-switching models with filtering and ambiguity	Discrete policy and supervisory states	Hedging demand, regime-risk premia, welfare and stability implications
Climate policy uncertainty	Textual analysis, supervised classification, embeddings, and asset-pricing tests	Uncertainty about carbon pricing, emission caps, disclosure, subsidies, and transition policy	Climate-policy uncertainty indicators, volatility effects, priced-risk tests
Derivatives-implied tax uncertainty	No-arbitrage identification from derivatives and underlying assets combined with panel econometrics	Investor-level tax expectations and tax uncertainty	Implied dividend tax penalty, tax uncertainty, effects on returns, payout, and investment

4 Modeling and Quantifying Regulatory Uncertainty and Its Implications

Building on the application areas discussed above, this section turns to the project-specific implementation of the framework. Table 3 provides a roadmap for the section by linking each project area to its methodological approach, the regulatory object under study, and the expected output. The table shows how the common framework is operationalized across modeling, measurement, and empirical analysis in the projects of the research unit.

4.1 Regulatory Uncertainty in Financial Decisions

We focus here on asset allocation in regulated environments in which investors and institutions face not only stochastic returns and cash flows, but also uncertainty about regulatory constraints, tax regimes, solvency requirements, or guarantee rules. The novelty does not lie in treating uncertainty itself as a primitive in the decision problem. Rather, it lies in specifying *regulatory* uncertainty as a primitive that can affect both the law of motion of payoffs and the feasible set induced by regulation, and in linking this specification to measurable regulatory signals and testable implications for portfolios, welfare, and prices. This approach separates financial risk, ambiguity about economic fundamentals, and uncertainty about regulatory parameters, interpretation, or enforcement.

Regulatory uncertainty can affect decisions through several channels: by changing perceived return dynamics and cash flows, by altering the feasible region induced by regulation, by changing beliefs about enforcement and regime persistence, or by affecting the value of instruments that provide regulatory or tax certainty. We distinguish between (i) a methodological component that develops asset allocation

models under ambiguity, learning, and regulatory constraints, and (ii) an applied component that tailors these models to taxation and insurance, including Solvency-II-type frameworks and pension systems. This structure is designed to deliver both theoretical mechanisms and application-specific, quantitatively interpretable implications.

State of the Art Classical portfolio choice models under risk use stochastic processes for prices and endowments in the tradition of Merton (1969, 1971). More advanced frameworks incorporate parameter uncertainty, model ambiguity, and learning, often relying on robust decision making, smooth ambiguity preferences, or Bayesian updating (Ellsberg 1961; Hansen and Sargent 2001; Klibanoff et al. 2005; Garlappi et al. 2007; Bäuerle and Mahayni 2024). Learning-based portfolio choice models provide an important benchmark for belief updating under partial information (Karatzas and Zhao 2001; Xia 2001; Björk et al. 2010; Bäuerle and Chen 2019). These approaches are central to our purposes, but they usually do not model regulatory uncertainty as an institutional object that can affect both payoff dynamics and regulatory constraints.

A related literature studies the impact of specific regulatory tools, such as Value-at-Risk or Expected Shortfall constraints, on optimal investment and asset prices (Basak and Shapiro 2001; Chen et al. 2018b, 2019; Bäuerle and Chen 2023). These models show how regulatory constraints shape portfolio choice, equilibrium prices, and welfare. However, the regulatory environment is often treated as fixed. This leaves open how investors and institutions behave when the regulatory parameters themselves, such as confidence levels, capital thresholds, solvency requirements, or guarantee specifications, are uncertain, evolving, or only partially observed.

In taxation, many optimal asset allocation models use deterministic tax rates or treat tax risk in a highly reduced form, for example by adding noise to after-tax cash flows without modeling the structure of the tax environment (Edmiston 2004; Niemann 2011; Gries et al. 2012; Niemann and Sureth 2013). This is insufficient to capture the multiple dimensions of modern tax systems and the interaction between tax uncertainty and cash flow uncertainty (Guenther et al. 2017; Jacob and Schütt 2020). The literature on tax rulings and tax incentives further emphasizes multi-component tax uncertainty and the design of instruments that provide tax certainty (Diller et al. 2017; Osswald and Sureth-Sloane 2024; Chen et al. 2025b).

On the insurance side, most contributions take regulatory frameworks as given, for example fixed Solvency-II-type Value-at-Risk or Expected Shortfall constraints, and study their implications for life insurance and pension products (Chen et al. 2018a, b, 2019; Branger et al. 2023). Less is known about the effects of uncertainty in regulatory parameters themselves, such as confidence levels, capital thresholds, or guarantee specifications, on collective investment, policyholder welfare, and insurer behavior. This gap motivates us to model regulatory uncertainty explicitly in constraints and guarantees. Existing analyses typically fix the regulatory environment and ask how agents respond; our perspective additionally asks how agents respond when the regulatory environment itself is partially unknown and evolves over time while agents learn about it from regulatory signals or observed policy actions.

Research Contributions and Perspectives Our research contributes to three key areas. First, we provide continuous-time asset allocation models in which regulatory uncertainty is formalized as ambiguity about the underlying asset dynamics and about regulatory regimes. The models build on smooth ambiguity preferences and Bayesian learning about unknown parameters, but apply these tools to regulatory environments in which uncertainty affects not only beliefs about payoffs but also the constraints under which decisions are made. This explicitly separates (i) financial risk, (ii) ambiguity about economic fundamentals, and (iii) ambiguity about the regulatory regime, and therefore yields a transparent mapping from regulatory uncertainty to portfolio demand, welfare effects, and pricing implications. It also allows us to separate attitudes toward financial risk from attitudes toward ambiguity and to quantify utility costs of regulatory uncertainty for investors and institutions. A further implication is that the models generate comparative statics that link observed portfolio shifts to changes in measured regulatory uncertainty, enabling empirical validation.

Second, we model regulatory uncertainty in constraints through worst-case conditional risk constraints and uncertain quantiles: Value-at-Risk (VaR) and Expected Shortfall (ES) thresholds, benchmark or guarantee levels, and solvency requirements are treated as random or partially observable processes (for example finite-state Markov chains or mean-reverting processes), with information updating over time. This delivers a unified language for regulatory uncertainty that nests deterministic constraints as a limiting case and accommodates both anticipated regulatory transitions (regime switching) and unforeseen changes (innovations) in constraint tightness. This generalizes standard VaR/ES-constrained portfolio problems by allowing for uncertainty in the level and timing of regulatory thresholds and links to tractable worst-case formulations (Bäuerle and Chen 2023; Chen et al. 2018a, b, 2025c).

Third, we develop applications in taxation and insurance that demonstrate how regulatory uncertainty in tax rules, risk constraints, capital requirements, and guarantees affects optimal portfolios and welfare. These applications quantify economically meaningful objects, such as welfare losses due to regulatory uncertainty and shadow costs of regulatory tightening. Such objects can be compared across institutions and regulatory settings and can be connected to empirical measures of regulatory uncertainty.

In taxation, a key application is the modeling of multi-component tax uncertainty in a continuous-time portfolio choice setting. We model an investor who finances a risky project (for example, R&D-intensive activities) with equity and debt and faces (i) stochastic statutory tax rates on profits and losses, (ii) uncertain loss offset provisions, and (iii) tax audit risk and enforcement intensity that depend on taxable income. This structure moves beyond one-dimensional "tax-rate risk" by capturing distinct sources of regulatory uncertainty that matter differently for downside risk, leverage incentives, and the valuation of tax shields. This approach yields a rich after-tax payoff structure in which profits and losses are taxed asymmetrically and post-audit tax payments are random. The investor can purchase an advance tax ruling that replaces random tax rates by fixed, contractible rates at an endogenous fee,

thereby trading off protection against tax uncertainty against the cost of obtaining tax certainty (De Waegenaere et al. 2007; Becker et al. 2017; Diller et al. 2017).

Interpreting advance tax rulings as instruments that transform tax-related regulatory uncertainty into priced contracts allows us to identify when and why tax certainty has value, and which components of tax uncertainty drive this value. We study the resulting risk-constrained asset allocation problem under a regulatory solvency constraint of Value-at-Risk type and characterize how tax uncertainty, debt ratios, and the design and pricing of advance tax rulings jointly affect optimal investment and firm value (Chen et al. 2019; 2025b). The model thereby delivers testable implications for how firms' leverage and investment respond to shifts in enforcement intensity and anticipated reform, and for how ruling fees should vary with the composition of tax uncertainty. Extensions incorporate behavioral preferences (for example Cumulative Prospect Theory) to analyze when loss-averse or target-driven investors value advance tax rulings more than standard expected utility maximizers.

In insurance, we study capital requirements and guarantee levels for collective investments under Solvency-II-type regulation, allowing for uncertainty in the regulatory parameters (Chen et al. 2018a, b, 2019; Branger et al. 2023). Collective pension and life insurance products are modeled via a collective utility function that aggregates heterogeneous policyholders with different degrees of risk aversions and contribution histories. Regulatory uncertainty enters through uncertain VaR or ES thresholds and through guarantee rules, for example ratchet-type guarantees in which the relevant regulatory default threshold depends on past fund values and is only revealed with a time delay. By combining parameter uncertainty about regulatory thresholds with delayed and state-dependent guarantee rules, we capture salient institutional features that are difficult to represent in models with fixed regulation. We will analyze optimal collective investment under such uncertain constraints from the perspectives of both the policyholders and the insurers, study how the distribution of guarantees and regulatory thresholds across sub-portfolios affects efficient risk sharing, and derive the implied welfare costs of regulatory uncertainty for policyholders, shareholders, and managers.

These studies provide quantitative benchmarks for the costs of regulatory uncertainty borne by insurers and policyholders. They also yield testable predictions for empirical studies that measure and price tax and regulatory uncertainty and examine the real effects of tax uncertainty (Eberbach et al. 2021; Fox et al. 2022; Jacob et al. 2022; Chen et al. 2025b; Gallemore et al. 2025).

4.2 Regulatory Uncertainty and Pricing of Spillover Risks in Networks

Regulatory interventions are a defining feature of modern economies. Trade policy, environmental regulation, and financial supervision are typically targeted at specific sectors, yet their economic and financial consequences often extend far beyond the directly affected industries. This is because firms and financial institutions are connected through complex networks of production linkages and financial exposures, which provide channels through which shocks can propagate across the economy. As a result, regulatory actions and, crucially, regulatory uncertainty can spread well beyond their original point of impact. Understanding how such uncertainty

is transmitted, amplified, or mitigated through economic and financial networks is therefore central to contemporary debates in macroeconomics, finance, and policy analysis. The project will analyze how regulatory uncertainty reshapes network structures and how these changes are reflected in asset prices, risk premia, and market dynamics. We also advance dynamic network methods to empirically identify and measure the effects of regulatory uncertainty transmitted through the network. The following subsection situates this research agenda in the existing literature and highlights key gaps that motivate our approach.

State of the Art Networks have become a unifying framework in finance and econometrics for representing cross-sectional interdependence, shock propagation, and systemic amplification in complex economic systems (Acemoglu et al. 2012; Carvalho 2014; Jackson and Pernoud 2021; Elliott and Golub 2022; Carvalho and Tahbaz-Salehi 2019). In asset pricing, network topology and agents' or firms' positions within the network are increasingly viewed as economically meaningful state variables that shape exposures and risk premia across the cross-section (Herskovic 2018; Ahern 2013; Antràs and Chor 2018; Gofman et al. 2020). On the empirical side, econometric research has developed tools to infer the topology of networks from data and to quantify time-varying spillovers, connectedness, and tail dependence at scale (Diebold and Yilmaz 2014; Hautsch et al. 2015; Betz et al. 2016; Chen and Schienle 2024). More recently, identification and inference have moved toward explicitly network-aware designs and high-dimensional estimation approaches that accommodate interference and evolving dependence structures (Angrist et al. 1996; Buse et al. 2022; Roth et al. 2023; Buse and Schienle 2019; Liang and Schienle 2019).

In finance, the research agenda builds on the growing literature on asset pricing in network economies, which links firms' positions in production and financial networks to expected returns and risk premia. Existing theoretical and empirical work shows that network characteristics such as concentration and the strength of bilateral relations are priced, as are centrality and upstreamness of assets, which reflect exposure to aggregate shocks and spillover risk (Ahern 2013; Antràs and Chor 2018; Herskovic 2018). Integrating these concepts into long-run risk models gives rise to a premium for uncertainty about the future network structure, which shapes the dynamics of cash flows. However, the role of regulatory uncertainty as a driver of network changes has received little attention so far. We address this gap by integrating regulatory uncertainty into network-based asset pricing frameworks.

Econometrically, we contribute to the literature on measuring and identifying spillovers, connectedness, and dynamic dependence structures in high-dimensional systems. A large body of work develops methods to estimate financial and macroeconomic networks from data, including variance-decomposition networks, impulse-response-based connectedness measures, and tail-risk networks (Diebold and Yilmaz 2014; Betz et al. 2016). More recent contributions extend these tools to time-varying and high-dimensional settings using shrinkage, penalization, and state-space approaches (Buse and Schienle 2019; Chen and Schienle 2024). Yet, identifying the causal impact of regulatory interventions in such environments remains challenging, as standard assumptions such as no interference across units are violated in network

settings (Angrist et al. 1996). While recent work proposes difference-in-differences designs and testing procedures adapted to networks, open issues remain regarding time variation, trend adjustment, and inference in large systems (Buse et al. 2022; Roth et al. 2023). We contribute by advancing identification and testing strategies that explicitly account for dynamic network dependence and regulatory uncertainty, thereby providing empirically implementable tools to quantify regulatory spillovers without imposing restrictive structural assumptions.

Research Contributions and Perspectives In this part, we investigate regulatory uncertainty in a network context with implications for both asset pricing and empirical measurement. Rather than treating regulation as a sequence of isolated policy shocks, we conceptualize regulatory uncertainty as a force that reshapes interdependencies across firms, sectors, and financial markets. This perspective shifts attention from individual exposures to the structure and evolution of networks as economically relevant state variables, thereby providing a unified framework for studying spillovers, risk transmission, and pricing effects in regulated economies.

From a finance perspective, the project integrates regulatory uncertainty and network dynamics into the analysis of priced risk. Economic networks evolve over time, and regulatory uncertainty can influence this evolution by changing production incentives, financial linkages, and the structure of economic interactions. Future network configurations matter for asset pricing because they shape the propagation of shocks, aggregate consumption dynamics, and the cross-sectional distribution of firms' exposures within the economy, including centrality, upstreamness, and other network-based dimensions of risk. By linking regulatory uncertainty to endogenous network formation, the project extends existing network-based asset pricing frameworks and identifies an additional channel through which policy uncertainty can affect expected returns beyond aggregate consumption risk alone. As an example of this transmission mechanism, consider an unexpected tightening of emissions regulation that directly affects a carbon-intensive upstream sector. The regulated firms face higher expected compliance costs, while downstream firms connected through input-output linkages may face higher input costs or disruptions in supply. Banks and other intermediaries exposed to these firms may in turn experience higher balance-sheet risk. The initial regulatory shock can therefore propagate through both production and financial networks and be reflected in the equity and credit prices of firms that were not directly regulated. If the timing or stringency of the regulation is itself uncertain, the same network links determine which firms are most exposed to regulatory news and where changes in required returns or risk premia may be strongest. Recent climate regulation provides concrete evidence for the production-network channel. (Shi et al. 2025) study the introduction of the EU Carbon Border Adjustment Mechanism (CBAM) and show that European firms sourcing inputs from non-EU suppliers in CBAM-affected industries experienced significantly negative abnormal stock returns around the political agreement on CBAM. Their findings provide direct evidence that the valuation effects of climate regulation can be transmitted through observed supplier-customer links. Consistent with a broader production-network transmission mechanism, (di Giovanni et al. 2025) show that shocks to EU climate policy spill over to foreign industries connected to EU sectors through in-

termediate-goods trade, while finding no significant spillovers outside these supply-chain linkages. Because the framework focuses on general mechanisms rather than specific regulatory episodes, it applies to a broad range of regulatory environments and policy settings.

On the econometric side, the research contributes to the measurement and identification of regulatory spillovers in dynamic networks. A central perspective is that regulatory interventions violate standard assumptions underlying causal inference when outcomes for any unit depend on its network position and on shocks to connected units. We address this challenge by advancing network-aware empirical approaches that allow regulatory effects and associated uncertainty to be quantified in large, evolving systems. In particular, we work with and extend the Diebold-Yilmaz framework of spillover connectedness in modeling dynamic networks to accomodate time variation and high-dimensional settings. Moreover, we develop techniques for identifying causal effects from suitably chosen subnetworks using variations in the timing between policy announcements and policy implementation. Thus we contribute along the following points: (i) estimation of evolving exposure networks, (ii) identification of regulatory shocks versus regulatory uncertainty effects, (iii) estimation of treatment intensity through network distance and exposures, (iv) testing whether returns or risk premia reflect direct and indirect regulatory exposure. Collectively across all four aspects, these methodological contributions strengthen the empirical foundations for analyzing policy interventions in interconnected environments including trade policy changes.

Taken together, the research perspectives emphasize transferability and generality. While motivated by prominent regulatory settings, the contributions are not tied to a particular policy domain or market. Instead, they provide conceptual and empirical tools that can be applied across a broad range of regulatory contexts, including trade policy, environmental regulation, and financial supervision. In this sense, we contribute to a broader understanding of how policy-induced uncertainty interacts with economic networks and how these interactions shape financial risk, asset prices, and market outcomes.

4.3 Regulatory Uncertainty with Regime Switches: Asset Allocation and Asset Pricing in Climate Finance and Insurance

We study regime-switching models as a natural framework for regulatory uncertainty when policy and supervisory environments change between discrete regulatory states. In climate finance and insurance, such regime changes may reflect shifts in carbon pricing, emissions caps, or transition mandates, as well as changes in financial regulation that affect capital requirements, risk limits, or product guarantees. We will consider different information structures concerning the timing, persistence, and economic consequences of regime changes. The analysis will be designed to examine (i) investors' optimal portfolio strategies and welfare, (ii) regime-dependent asset prices and risk premia, and (iii) the implications of regulatory regimes for guarantee provision, insurer behavior, and financial stability.

The same regime-switching structure therefore connects asset allocation and asset pricing. Regulatory regimes may affect prices through regime-dependent expected

cash flows, volatilities, stochastic discount factors, and intermediary constraints. In climate applications, a transition to a more stringent policy regime may reduce the expected cash flows of carbon-intensive firms, increase hedging demand for green assets, and generate a regime-risk premium. Such a premium arises when innovations in the regulatory regime or in beliefs about regime transitions covary with marginal utility, worsen aggregate investment opportunities, or tighten intermediary constraints in adverse states. In a reduced-form empirical implementation, filtered regime probabilities and revisions in transition probabilities around regulatory announcements can be related to time-series and cross-sectional variation in returns. This extension brings the regime-switching analysis directly in line with the broader asset-pricing agenda of the framework.

State of the Art Regime-switching models are widely used to describe changes in macroeconomic or financial environments. In the context of regulatory uncertainty, they are particularly suited to capture discrete changes in policy and supervisory regimes, such as the introduction or tightening of capital regulations or climate policies (Ang and Timmermann 2012; Guidolin and Timmermann 2007; Liu 2011; Honda 2003; Sotomayor and Cadenillas 2009; Bo et al. 2019; Capponi and Figueroa-López 2014; Korn et al. 2017). Existing work has used regime shifts to represent changes in risk premia, volatilities, or default intensities, but has typically not combined these with endogenous portfolio choice under explicit regulatory constraints, nor with systematic learning about the prevailing regulatory regime and its transmission into asset dynamics (Bäuerle and Rieder 2007, 2020; Chen and Epstein 2002; Chen et al. 2011). Moreover, even when asset-price parameters vary across regimes, the regulatory origin of regime changes and the resulting pricing of regulatory regime risk are often not the central objects of analysis.

In climate finance, regime changes are a natural way to formalize shifts in climate policies, such as the adoption of more stringent emissions caps or carbon prices (Nordhaus 1992b; Blyth et al. 2007; Szolgayova et al. 2008; Linnerud et al. 2014; Boomsma and Linnerud 2015). These models complement approaches that treat climate risk as a long-run growth risk (Bansal et al. 2016, 2019; Rudebusch 2019; Barnett 2023; Giglio et al. 2021). A remaining gap is to integrate policy-driven regime changes jointly with regulated portfolio constraints and insurance-style guarantee features, and to quantify the resulting portfolio, pricing, welfare, and stability implications under partial observability of regimes.

Research Contributions and Perspectives Our project is designed to develop a unified regime-switching approach to regulated asset allocation and asset pricing in climate finance and insurance. First, we will consider continuous-time portfolio problems in which asset-price and cash-flow dynamics depend on latent policy and regulatory regimes. Applications include climate-transition settings with heterogeneous assets, such as brown and green assets, and environments in which capital regulation or supervisory intensity changes across regulatory states (Ang and Timmermann 2012; Guidolin and Timmermann 2007; Liu 2011; Bo et al. 2019; Capponi and Figueroa-López 2014). A finite-state regime process can jointly govern expected returns, cash-flow growth, volatilities, transition intensities, and regulation-induced

constraints. Under partial information, investors use observed market and regulatory signals to update filtered probabilities of the latent regimes, which become additional state variables in the portfolio problem. The key object is the joint evolution of investment opportunities and regulation-induced constraints across regimes, which makes it possible to derive portfolio demand, hedging demand, and exposure to regulatory regime risk. In an equilibrium extension, the marginal-utility process can be used to characterize the stochastic discount factor and the compensation required for exposure to regime changes.

Second, the project incorporates learning and ambiguity about regimes and their economic meaning. In many settings, investors and institutions observe market outcomes but only imperfectly infer the current policy regime, and the mapping from regulatory decisions to asset dynamics may itself be uncertain. We therefore aim to combine filtering of the latent regime with learning about regime-dependent parameters and to allow for ambiguity when transition probabilities or the regime-to-dynamics mapping are incompletely specified (Bäuerle and Rieder 2007, 2020; Chen and Epstein 2002; Chen et al. 2011; Bäuerle and Mahayni 2024). This structure separates risk conditional on a known regime, uncertainty about the prevailing or future regime, and ambiguity about the model linking regulatory regimes to economic outcomes. It can thereby provide utility-based measures of the cost of regulatory uncertainty and comparative statics for the effects of changes in regime persistence, observability, and ambiguity.

Third, we aim to extend the regime-switching framework to regulated constraints and insurance guarantees. In life-insurance and pension settings, relevant constraints may switch across supervisory states, for example through changes in guarantee levels, capital thresholds, or downside-risk measures such as Value-at-Risk or Expected Shortfall. These features are modeled as regime-dependent and may be observed only with delay or inferred from regulatory signals. The resulting portfolio and guarantee decisions can then be studied from the perspectives of policyholders, insurers, and regulators (Chen et al. 2018a, b, 2019; Branger et al. 2023). The framework is designed to generate quantitative predictions for how policy-driven regime risk affects portfolio allocations, guarantee provision, welfare, regime-risk premia, and the probability that regulatory constraints bind. It also permits an analysis of the conditions under which discrete regulatory changes amplify or dampen systemic vulnerability.

4.4 Climate Policy Uncertainty

Climate policy uncertainty is a central dimension of regulatory uncertainty in the transition to a low-carbon economy. Beyond physical climate risks, economic agents face uncertainty about the timing, scope, and design of regulatory interventions (such as emissions trading schemes, carbon taxes, disclosure requirements, and green investment mandates). This uncertainty affects investment decisions, portfolio choice, and ultimately asset prices. Addressing these effects requires an integrated perspective that combines measurement, modeling, and empirical analysis of climate policy uncertainty, and that explicitly accounts for the role of financial intermediaries in transmitting or mitigating policy-induced uncertainty.

A central element of our framework is the conceptual distinction between climate policy expectations and climate policy uncertainty. Climate policy *expectations* refer to the anticipated direction or level of future regulatory interventions. For instance, a market consensus that carbon prices in an emissions trading scheme are likely to rise over the next decade constitutes an expectation. Such shifts in the 'first moment' primarily influence firms' expected future cash flows and fundamental valuations by altering the cost-benefit structure of carbon-intensive versus green activities.

In contrast, climate policy *uncertainty* captures dispersion in beliefs about, or ambiguity surrounding, future policy realizations. This involves uncertainty about the precise timing of new disclosure requirements, the legal durability of green subsidies, or the specific sectoral coverage and enforcement of adjustment mechanisms. This 'second moment' of regulatory risk is economically distinct: while the expected policy level affects expected cash flows, the uncertainty surrounding realizations influences risk premia, increases hedging demand, and raises the real option value of waiting for irreversible investment decisions. By disentangling these dimensions, our approach provides a framework for studying which aspects of climate policy act as priced risk factors in equilibrium.

Relative to existing news-based climate policy uncertainty indices, our measurement approach aims to add three dimensions. First, it will separate effects of expected policy direction from policy uncertainty. Second, it will classify texts by policy instrument, such as carbon pricing, emissions trading, disclosure, subsidies, and adjustment mechanisms. Third, it will combine newspaper coverage with other structured information sources such as market metrics. It can therefore be extended to include information from, for example, regulatory documents, parliamentary debates, central bank and supervisory publications, or firm disclosures. Methodologically, we will complement dictionary-based counts with advanced supervised classifiers, transformer-based text embeddings, and measures of their variation. This will allow us to study not only the extent to which climate policy is subject to uncertainty, but which policy instruments generate uncertainty and whether this refined uncertainty has different pricing implications than standard measures.

The following subsection situates the outlined research agenda within the existing literature and highlights the key gaps and unresolved questions that motivate the proposed research program.

State of the Art The literature on climate change and financial markets has made substantial progress in modeling and pricing climate risk, particularly through dynamic integrated assessment models and asset pricing frameworks that link economic activity, emissions, temperature dynamics, and disaster risk (Nordhaus 1992a; Bansal et al. 2016, 2021; Giglio et al. 2021). These approaches have shown that climate risk can be a priced source of uncertainty, especially in settings with long-run risks, rare disasters, or preferences for early resolution of uncertainty (Giglio et al. 2021). More recent contributions emphasize transition risk, highlighting that changes in regulation, technology, and consumer preferences during the transition to a low-carbon economy can have first-order effects on firms' cash flows and asset valuations (Barnett 2023; Hsu et al. 2023; Acemoglu et al. 2023). Much of the existing literature conflates these dimensions by treating climate policy as a deterministic

path or a simple stochastic process. Consequently, it focuses on the first-moment effects of a transition—such as the impact of an anticipated carbon tax on firm profitability—while neglecting the second-moment impact arising, e.g., from the nonlinear path of policy implementation and the threat of sudden regulatory updates or reversals.

If climate policy uncertainty is considered at all, it is proxied by carbon prices or reduced-form volatility measures, implicitly assuming that market prices sufficiently reflect policy-related uncertainty (Andersson et al. 2016; Yang et al. 2008). This approach is problematic, as carbon prices are shaped not only by expectations about future regulation but also by market design and institutional features of emissions trading systems, especially in their early phases. Moreover, carbon prices reflect the objectives, constraints, and beliefs of the investors and intermediaries active in these markets. Consequently, variation in carbon prices may capture changes in risk-bearing capacity, regulatory constraints, or market structure in addition to climate policy expectations and climate policy uncertainty. In response, a growing empirical literature has begun to extract climate-related policy uncertainty from textual information, using news-based indicators to capture uncertainty surrounding political debates, regulatory interventions, and policy timing (Baker et al. 2016; Engle et al. 2020; Ilhan et al. 2021; Gavriilidis 2021). While these measures provide a richer representation of policy uncertainty than price-based proxies, important challenges remain regarding their interpretation, comparability, and integration into financial econometric models, particularly when linking policy uncertainty to volatility dynamics, risk premia, and asset prices.

Beyond measurement, an important strand of the literature investigates how climate-related uncertainty is reflected in asset prices, volatility dynamics, and risk premia. Recent empirical work links climate and policy-related uncertainty to realized volatility and variance risk premia, highlighting that uncertainty about future policy actions can affect both expected returns and risk compensation (Engle et al. 2020; Ilhan et al. 2021; Conrad and Schienle 2020). Incorporating climate policy uncertainty into financial econometric models, however, raises several non-trivial challenges, as policy-related indicators often differ in frequency, persistence, and information content from standard financial variables and may also react endogenously to market conditions and policy announcements. At the same time, a large literature studies the effects of regulatory uncertainty on financial intermediaries, documenting that uncertainty about regulatory regimes can impair information production, reduce lending and investment, and alter risk-taking incentives (Bernanke 1983; Mahoney 2019; Bowe et al. 2023; Chen et al. 2023). While these studies emphasize the role of intermediaries in transmitting economic policy uncertainty more broadly, evidence on how climate policy uncertainty operates through the financial sector remains scarce. Existing contributions provide only indirect insights, for example through productivity effects or disclosure-related uncertainty resolution (Ren et al. 2022; Becker et al. 2022), leaving open (i) how intermediaries update and produce information about climate policy, (ii) whether they mitigate uncertainty for households and firms, (iii) how their constraints affect their ability to do so, and (iv) how these channels feed back into risk premia and asset prices.

Research Contributions and Perspectives Our research contributions and perspectives span four closely connected dimensions that jointly address how climate policy uncertainty is measured, modeled, and priced. First, we will advance the measurement of climate policy uncertainty by developing news-based indicators that capture the forward-looking and multidimensional nature of regulatory uncertainty. Building on recent advances in textual analysis and machine learning, we propose an approach for extracting uncertainty from large-scale newspaper corpora by combining supervised classification techniques with embedding-based measures of disagreement across texts (Baker et al. 2016; Gentzkow et al. 2019; Engle et al. 2020; Ilhan et al. 2021; Gavriilidis 2021). Focusing on climate policy related to CO_2 emissions, these measures complement price-based proxies and can be benchmarked against observable developments in emissions markets and policy events. A central objective of this line of research is to assess how different sources of textual information and levels of aggregation affect the empirical performance and interpretability of policy uncertainty measures, and to develop robust ways to incorporate them into financial econometric models (Conrad and Schienle 2020). We propose to advance the measurement of regulatory risk by developing indicators that capture both the level of regulatory uncertainty and its variation. Using supervised classification and transformer-based embeddings, we aim to distinguish between directional signals (shifting policy expectations) and ambiguity signals (increasing policy uncertainty regarding timing or scope). This allows for a more granular identification of whether news coverage reflects a likely policy shift or a mere increase in information uncertainty.

Second, we will incorporate climate policy uncertainty into asset pricing models that analyze the transition to a low-carbon economy. In these models, regulatory measures such as taxes, emission caps, or subsidies are allowed to vary stochastically over time, reflecting uncertainty about political decisions and their implementation (Hsu et al. 2023; Acemoglu et al. 2023). This approach provides a link between political processes and asset prices and allows us to study how climate policy uncertainty affects risk premia across assets that differ in their exposure to transition risk. Theoretical perspectives include both exogenously evolving regulatory uncertainty and settings in which regulatory uncertainty arises endogenously from political costs faced by decision makers (Pástor and Veronesi 2012, 2013), generating testable implications for the pricing of climate policy risk during the transition (Giglio et al. 2021). For example, by treating carbon taxes or emission limits as stochastic rather than fixed, our models provide a formal basis for analyzing how uncertainty about the future permanence of a regulatory measure affects valuations independently of the policy's current level.

Third, we will study financial intermediaries as a key channel through which climate policy uncertainty affects households' investment decisions and financial markets. While sustainability reporting and enhanced disclosure mandates have improved households' ability to judge firm-level alignment with expected climate policy, climate policy uncertainty itself remains a 'black box'. Standardized corporate disclosures are effective at quantifying policy expectations, but offer little transparency regarding risks such as the perceived ambiguity surrounding the timing, legal durability, or enforcement stringency of future rules. This highlights the impor-

tance of financial intermediaries as critical information producers who look beyond corporate filings to decipher complex regulatory signals. Our perspective emphasizes that intermediaries can both mitigate and amplify policy uncertainty, depending on their ability to produce information, their incentives, and their organizational characteristics. By distinguishing between delegated and direct investment in green assets, we propose to analyze how climate policy uncertainty shapes portfolio allocation decisions and how intermediation interacts with households' preferences for sustainable investment (Gutsche and Ziegler 2019; Holzmeister et al. 2023). Existing evidence shows that regulatory uncertainty can impair information production, reduce lending and investment, and alter risk-taking incentives in the financial sector (Bernanke 1983; Mahoney 2019; Bowe et al. 2023; Chen et al. 2023). A central objective of this line of research is to identify potentially non-linear effects of climate policy uncertainty on delegated investment and to assess when intermediation facilitates, and when it hinders, the allocation of capital toward greener firms.

Fourth, we will investigate the asset pricing implications of climate policy uncertainty, both in aggregate and in the cross-section of assets. Combining our proposed uncertainty measures with theoretical predictions and intermediation data, we assess whether climate policy uncertainty constitutes a priced risk factor (Engle et al. 2020; Ilhan et al. 2021). Empirical perspectives include time-series analyses linking policy uncertainty to volatility dynamics and variance risk premia (Conrad and Schienle 2020), as well as cross-sectional tests of expected returns for assets with different exposures to climate policy risk (Giglio et al. 2021). Disentangling climate policy risk from climate policy expectations allows us to test empirically whether climate policy uncertainty acts as a priced risk factor that is distinct from the expected cash flow effects of expected policy changes. This is essential for understanding why, e.g., two firms with identical exposure to an expected carbon tax may still exhibit different expected returns due to their differing sensitivity to climate policy uncertainty. A particular focus is on understanding how the price of climate policy uncertainty varies with the degree of financial intermediation, and whether uncertainty is priced differently when it is borne directly by households versus when it is potentially reduced through delegated investment (Becker et al. 2022).

4.5 Derivatives-Implied Tax Uncertainty

Taxes on dividends, capital gains, and interest income influence both portfolio allocation and corporate financial policy. Since tax expectations depend not only on changes in the tax code and enforcement practices but also on uncertainty in legislative, administrative, and judicial processes, it is essential to study forward-looking tax expectations and tax uncertainty. However, measuring both dimensions empirically is challenging, as they are difficult to observe and disentangle.

To address this, we adopt a no-arbitrage-based approach to extract investor-level tax expectations and the associated tax uncertainty from financial market prices in two steps (Eberbach et al. 2021). In essence, we extract market-implied tax rates by constructing portfolios that generate economically equivalent pre-tax cash flows but that are subject to divergent tax treatments. Consequently, the portfolios give rise to different after-tax cash flows. Under no-arbitrage conditions, the price

difference between these portfolios reflects the market-implied expected tax burden. This approach allows us to avoid restrictive general equilibrium assumptions, relying instead on the absence of arbitrage opportunities.

Identifying tax expectations and tax uncertainty empirically requires two steps. First, tax expectations must be inferred from the prices of derivatives and the prices of their underlyings at each point in time. Second, the variation in these implied tax expectations over time can be used to construct a measure of tax uncertainty. This measure provides the basis for examining the impact of tax expectations and tax uncertainty on asset prices, as well as on firms' investment and payout policies. From an asset pricing perspective, tax uncertainty may affect equilibrium risk premia. From a corporate finance perspective, tax uncertainty may influence firms' payout and investment decisions by changing the relative attractiveness of distributing versus retaining internal funds.

State of the Art Economic theory suggests that taxes influence a wide range of corporate decisions, including investment and payout behavior (Brennan 1970; Miller and Scholes 1978; Auerbach 1979; Chetty and Saez 2010). Empirical evidence supports this view, indicating that dividend taxes, capital gains taxes, and taxes on interest income affect both dividend payments and share repurchases (e.g., Chetty et al. 2005; Moser 2007; Jacob and Jacob 2013; Hanlon and Hoopes 2014; Jacob and Michaely 2017), as well as corporate investment decisions (Yagan 2015; Moon 2022).[1] However, the magnitude and consistency of these tax effects remain subject to debate. Estimated average effects on corporate policy are often modest and vary considerably across studies. This lack of consistent and sizeable effects could be due to the focus on statutory tax parameters, instead of forward-looking tax expectations and tax uncertainty. Statutory rates lack the time-series variation necessary to capture shifting expectations and uncertainty. They may therefore provide an incomplete picture of tax-related decision-making, since investment and payout decisions are made based on expectations about the *future* tax treatment of dividends, capital gains, or interest income. Consequently, expected future tax rates and the uncertainty surrounding them are likely to be of first-order importance for asset prices as well as for firms' dividend payout and investment decisions.

Yet, taxes have been shown to shape payout behavior and corporate investment. For example, Moser (2007) and Jacob and Jacob (2013) find that higher dividend taxes are associated with reduced dividend payments and increased share repurchases. This finding is consistent with survey evidence from Brav et al. (2005), who report that roughly one-third of financial executives in their survey consider tax considerations to be important in shaping payout policy. However, these studies do not take a forward-looking perspective and thus do not capture tax expectations and tax uncertainty.

Our perspective on investment and payout decisions is motivated by evidence from Brav et al. (2005), who find that firms often make investment and payout de-

[1] For further evidence on investor-level taxes and market outcomes, see Sialm (2009) on asset pricing, Thornock (2013) on short selling, Ohrn and Seegert (2019) on mergers and acquisitions, and Li et al. (2021) on idiosyncratic volatility.

cisions simultaneously, treating them as alternative uses of internal funds. Similarly, Jensen et al. (1992) document a negative relationship between dividend payments and corporate investment, suggesting a trade-off between returning capital to shareholders and reinvesting in the firm. Tax expectations and tax uncertainty may tilt this trade-off by changing the relative after-tax attractiveness of payouts versus retention.

At the investor level, empirical work also typically uses current statutory tax rates to proxy taxation (e.g., Dyreng et al. 2008), occasionally incorporating investor characteristics or focusing on specific investor types. Other studies take an indirect approach by comparing stock attributes such as dividend yield or ownership concentration across tax clienteles (Dai et al. 2008; Sialm 2009). For comprehensive overviews, see Graham (2003), as well as Becker et al. (2013), Steinmüller et al. (2018), and Jacob (2021). On the theoretical side, prior work shows that increasing dividend tax penalties reduces the attractiveness of dividend payouts for shareholders (Brennan 1970; Auerbach 1979; Chetty and Saez 2010). None of these studies analyze tax expectations and tax uncertainty.

A related strand of literature investigates the effects of volatility in effective corporate tax rates—often as a proxy for tax uncertainty—on firm-level investment behavior and risk-taking (e.g., Edmiston et al. 2003; Guenther et al. 2017; Jacob and Schütt 2020; Fox et al. 2022), relying on observable statutory tax rates and their changes but largely ignoring investor-level tax uncertainty and forward-looking tax expectations. This omission is surprising, given the well-established insight in financial economics that investors' expectations about future conditions are *central* to decision-making. With respect to taxes, investors must anticipate the tax treatment of future dividends, capital gains, or interest income—taxes that materialize at the time of payout, share repurchase, or asset sale—in order to evaluate the after-tax value of their investment strategies. Consequently, investors must form expectations about future tax rates, and these expectations and the uncertainty surrounding them drive their decisions regarding portfolio allocation and thus drive asset prices. Linking firm-level and investor-level tax expectations and tax uncertainty is crucial, since there is an interdependence between the two: Firms anticipate investor considerations and reflect them in their payout policy and real investment decisions. Conversely, investors form expectations about firms' returns based on real investment and payout policies and make portfolio decisions accordingly.

Empirical tax research has only recently begun to explore the role of tax policy expectations and uncertainty. Among the few exceptions, Hassan et al. (2019) construct a firm-level policy risk measure based on textual analysis of quarterly earnings calls, capturing references to political risk, including tax policy. Gallemore et al. (2025) build on this approach to study tax policy sentiment and uncertainty around the U.S. election and the Tax Cuts and Jobs Act. While this approach captures firm-level tax expectations from text data, it does not address investor-level tax expectations or how such expectations are reflected in market prices. In contrast, our approach differs in two key respects. First, we will focus on investor-level taxes, building on prior evidence that such taxes influence corporate payout and investment decisions. Second, we will utilize capital-market data to identify how expectations about investor-level tax rates (first moment) and the uncertainty surrounding them (second moment) are reflected in market prices and how they shape corporate be-

havior. Our prediction that tax expectations influence firm decisions is supported by findings on tax misperception. Using survey and administrative data, Heinemann-Heile et al. (2024) show that firms often misperceive their effective tax rates, with complexity being a key driver of this bias. Such misperception, in turn, affect investment decisions (for an overview, see Blaufus et al. 2022). While this evidence highlights the importance of tax-related beliefs for firm behavior, it does not provide forward-looking, market-based proxies for investor-level tax expectations, nor for their impact on asset pricing and firm-level investment behavior. By extracting these parameters directly from security prices, we will provide forward-looking, market-implied measures that capture the real-time transmission of tax risks into security prices. Our approach will enable a clean identification of the transmission channels through which regulatory uncertainty constitutes a priced risk factor in asset returns and influences the corporate trade-offs between payout and investment decisions.

Relatedly, Fleckenstein et al. (2019) use price differentials between taxable and tax-exempt bonds to infer tax uncertainty. In doing so, they build on a substantial literature that exploits yield spreads between taxable and tax-exempt bonds (Poterba 1989; Ang et al. 2010). However, their approach does not allow for a clean identification of forward-looking tax expectations. First, bond coupons—unlike dividends—are typically predetermined and accrue linearly over time, which means that the observed spread reflects a mix of current and anticipated future tax effects. Second, the classical literature on the 'muni puzzle' demonstrates that raw yield spreads between taxable and tax-exempt debt are frequently contaminated by non-tax factors such as liquidity premiums, idiosyncratic default risk, and embedded call options. Ang et al. (2010) specifically highlight the sensitivity of individual retail investors to tax-related price discounts in market discount bonds, which can result in implicit tax rates that far exceed statutory levels. Third, bond prices can reflect tax uncertainty from both the issuer side and from the investor side, making the resulting price differential an ambiguous signal of market expectations.

While a number of optimal asset allocation models incorporate taxes using deterministic (e.g., Seifried 2010; Chen et al. 2019) or stochastic tax rates (e.g., Sialm 2009), these frameworks typically rely on exogenous assumptions rather than market-based, forward-looking tax information. To the best of our knowledge, prior work has not extracted implied investor-level tax expectations from derivatives prices and used the resulting measures to study both asset prices and firm policies. Our approach thus complements prior firm-level studies by providing a market-based proxy for investor-level tax expectations, enabling a new perspective on how tax-related beliefs are priced and how they shape corporate behavior.

Research Contributions and Perspectives We will build on Eberbach et al. (2021) and use a novel, theoretically grounded, firm-specific measure to extract investor-level tax expectations from derivatives prices. This approach combines two economically equivalent trading strategies that differ only in their tax treatment. Their price differences reflect expected tax burdens and yield a market-implied tax penalty. We first will recover market-implied tax expectations by comparing dividend futures with a synthetic replication of dividends using a portfolio of put options, call options, and the underlying security (an index or a single stock).

Dividend futures represent a direct claim to cumulative gross dividends and are inherently tax-free. In contrast, the replication portfolio reflects net dividends, as it incorporates both dividend taxes (τ_D) on distributions and capital gains taxes (τ_C) on the underlying asset. This allows us to isolate the dividend tax penalty $dtp = 1 - \frac{1-\tau_D}{1-\tau_C}$ as an indicator of the relative tax disadvantage of dividends versus capital gains. Unlike statutory rates, this measure is forward-looking and captures the market's anticipation of legislative shifts and judicial rulings at any point in time.

Using the dividend tax penalty, we then will construct our tax uncertainty measure by analyzing the time-series variation of dtp. This second moment captures perceived volatility in expected tax burdens and reflects both the likelihood and the timing of future tax changes due to legislative or administrative developments.

These measures enable us to examine the transmission of tax-related regulatory uncertainty through three primary channels. First, we will focus on asset pricing and asset returns: We will test whether tax uncertainty acts as a priced risk factor in equilibrium. Using Fama-MacBeth regressions, we investigate whether assets with high sensitivity to shifts in the implied tax penalty command a risk premium. This approach builds on evidence that investor taxes are a determinant of the equity risk premium and can resolve asset pricing puzzles related to the dividend term structure. Second, we aim to address payout policies: We will analyze how shifts in the dtp influence corporate distribution choices. Theoretical models suggest that a higher expected tax burden on dividends should tilt firms away from dividend payouts towards more tax-efficient alternatives, such as share repurchases or internal retention. Third, we aim to explore how tax uncertainty affects real investment by increasing the value of flexibility. Using a panel of European firms, we will examine the relationship between the implied dividend tax penalty and firms' payout and investment policy. Since many capital expenditures are irreversible, heightened uncertainty may prompt firms to delay projects or accumulate precautionary cash buffers.

A higher expected tax burden on dividends may shift firms away from dividend payouts toward retention or real investment, or toward more tax-efficient payout channels such as share repurchases. Tax uncertainty may have a separate effect by increasing the value of flexibility (Niemann 2011; Gries et al. 2012; Niemann and Sureth 2013), and by changing the relative attractiveness of irreversible investment and immediate payout. Ultimately, this research aims to contribute to a better understanding of how tax policy design and uncertainty affect capital markets and corporate decisions among investors, policymakers, and regulators alike.

5 Conclusions and Outlook

In this article we develop a programmatic conceptual framework for studying regulatory uncertainty in asset allocation and asset pricing. The central argument is not that regulatory uncertainty is wholly separate from broader economic policy uncertainty, but that it constitutes an analytically distinct component that can be identified by the institutional object to which the uncertainty relates. Uncertainty about reg-

ulatory design, timing, parameters, interpretation, and enforcement directly shapes cash flows, beliefs, feasible choice sets, and intermediary capital, liquidity, leverage, and profitability constraints. Focusing on these objects helps distinguish regulatory uncertainty from broader uncertainty about the political and macroeconomic environment.

The framework connects the sources of regulatory uncertainty to their entry points into financial models, their transmission channels, their empirical measures, and their economic outcomes. It also clarifies an important asset-pricing distinction. Regulatory uncertainty may be reflected in asset prices whenever it affects expected cash flows, constraints, or discount rates. It commands a risk or ambiguity premium only under stronger conditions, for example when regulatory shocks covary with marginal utility, affect aggregate investment opportunities or intermediary balance-sheet capacity, tighten constraints in adverse states, or cannot be diversified away because they operate at the sectoral or economy-wide level.

The framework thereby provides a common language for connecting theoretical modeling, measurement, and empirical analysis. Regulatory uncertainty can be represented through stochastic regulatory regimes, ambiguity, learning, uncertain constraints, tax rules, or changing network exposures. It can be measured using textual indicators, market-implied quantities, surveys, regulatory documents, and high-dimensional data. These measures can in turn be linked to portfolios, asset prices, risk premia, investment, payout decisions, risk sharing, and regulatory arbitrage. The selected application domains of sector-specific regulation, climate regulation, and taxation, together with the project illustrations involving networks, regime switching, insurance, and derivatives-implied tax uncertainty, demonstrate how this common structure can be adapted to different institutional settings.

Several priorities follow for future research. First, empirical measures should more sharply separate expected regulatory changes from uncertainty surrounding their timing, scope, implementation, and enforcement, while also distinguishing regulatory uncertainty from broader economic policy uncertainty. Second, theoretical and empirical work should test more directly when regulatory uncertainty is priced rather than merely incorporated into expected cash flows. Third, research should examine how interactions across regulatory domains propagate through firms, intermediaries, and economic networks and affect investment, risk sharing, and financial stability. The projects of FOR 5583 provide one set of illustrations of how this research agenda can be operationalized. From a policy perspective, the framework also highlights the potential value of predictable regulatory design, communication, and enforcement, while recognizing that the costs of regulatory uncertainty must be evaluated against the benefits of regulatory flexibility and adaptation.

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Declarations

Ethics Approval and Consent to Participate Not applicable. This study does not involve human participants or animals.

Consent for Publication Not applicable.

Conflict of interest N. Bäuerle, N. Branger, A. Chen, M. Gehde-Trapp, A. Mahayni, M. Schienle and C. Sureth-Sloane declare that they have no competing interests.

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