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TAMING THE ELECTRICITY MARKET ROLLER COASTER? – A SYSTEMIC ANALYSIS OF CONTRACTS FOR DIFFERENCE AS A RISK-HEDGING INSTRUMENT

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08.05.2026

The Idea

CfDs hedge Revenue Risks

- Guarantee fixed revenue for entire contract duration
- Protection especially against long-term market value uncertainty

Revenue Risks affect Cost of Capital

Reduced lifetime revenue uncertainty

→ Lower risk of default on debt

→ Lower cost of debt

→ Lower overall cost of capital (WACC)

Idea: Integrated quantitative systemic assessment of both effects

Our Approach

1. Run greenfield **system-cost-optimization model** (*PyPSA-EUR*)
2. Calculate **lifetime revenues and their uncertainty** under different CfD schemes
3. Calculate **updated WACC** based on revenue uncertainty under CfD schemes with analytical model
4. Run **model scenarios** with WACC under CfDs

Sources of Risk in the Model:

- Uncertain production **volume** due to uncertain future weather, represented by 35 weather years
 - Uncertain market **price** for produced electricity, represented by three levels of natural gas prices
 - Uncertainty about future **political market intervention**, quantified in separate scenario
- Incomplete risk sources in our model
- Results on risk premia as lower bound

Three types of CfDs

Production-based CfD

- Production-based CfD payments
- Only hedges **price risk**

Production-independent CfD

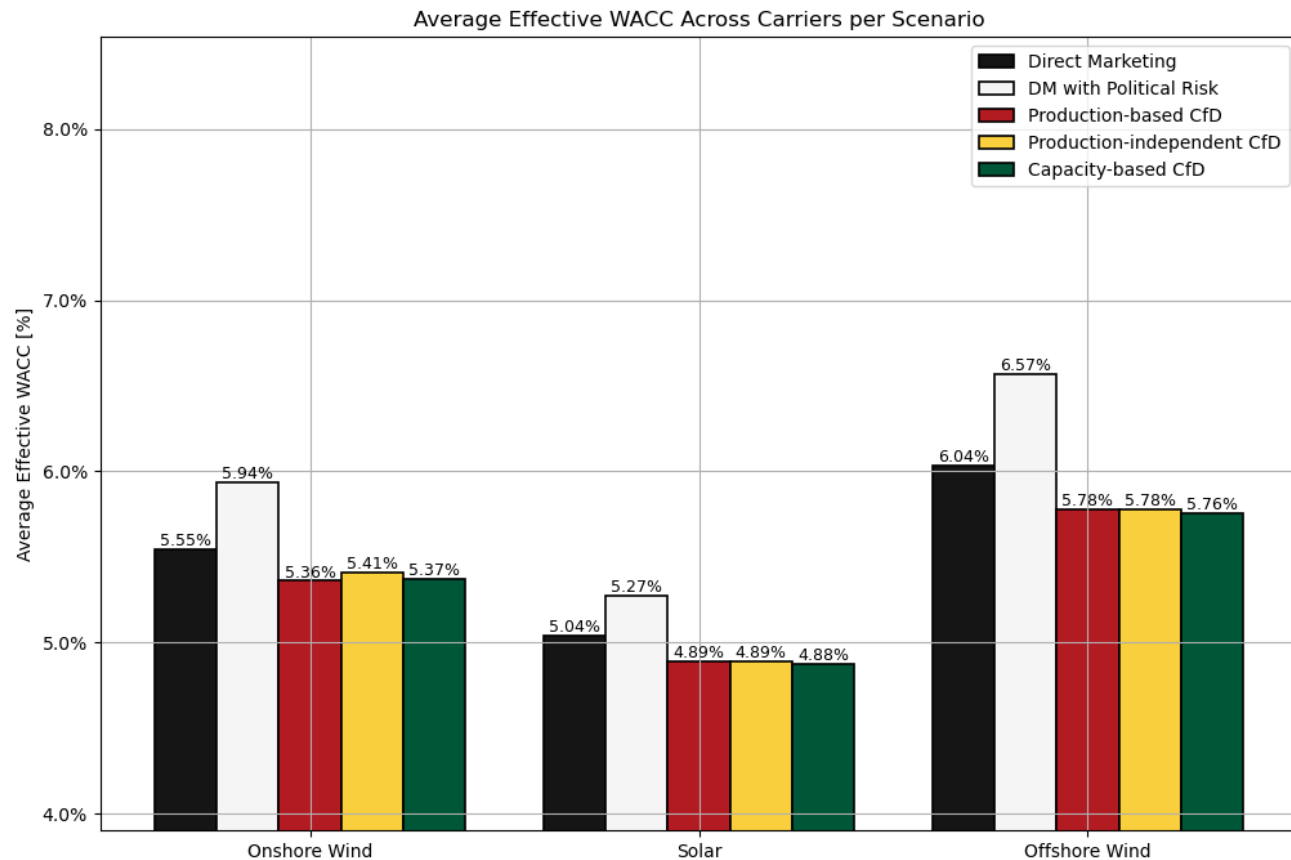
- CfD payments based on virtual reference profile
- Only hedges **price risk**, introduces additional **basis risk**

Production-independent CfD with capacity component

- Capacity payment to generator, clawback based on reference profile
- Hedges **price and volume risk**, adds additional **basis risk**

→ **Strike prices defined such that average state payments are zero**
No electricity market distortion → Modeling results remain interpretable

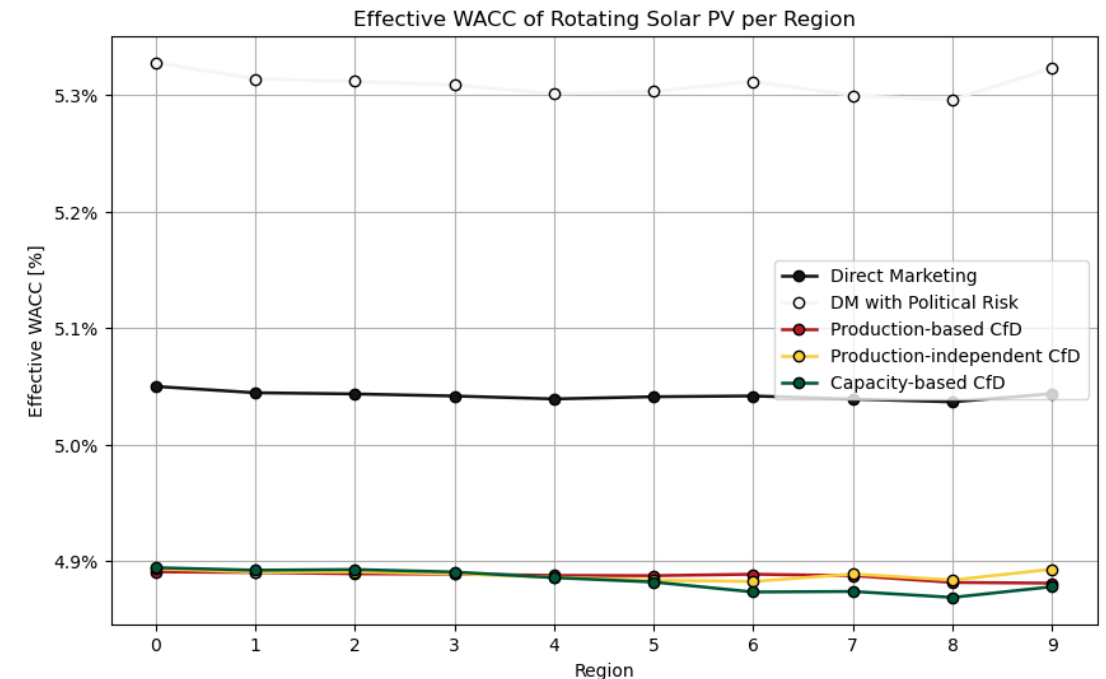
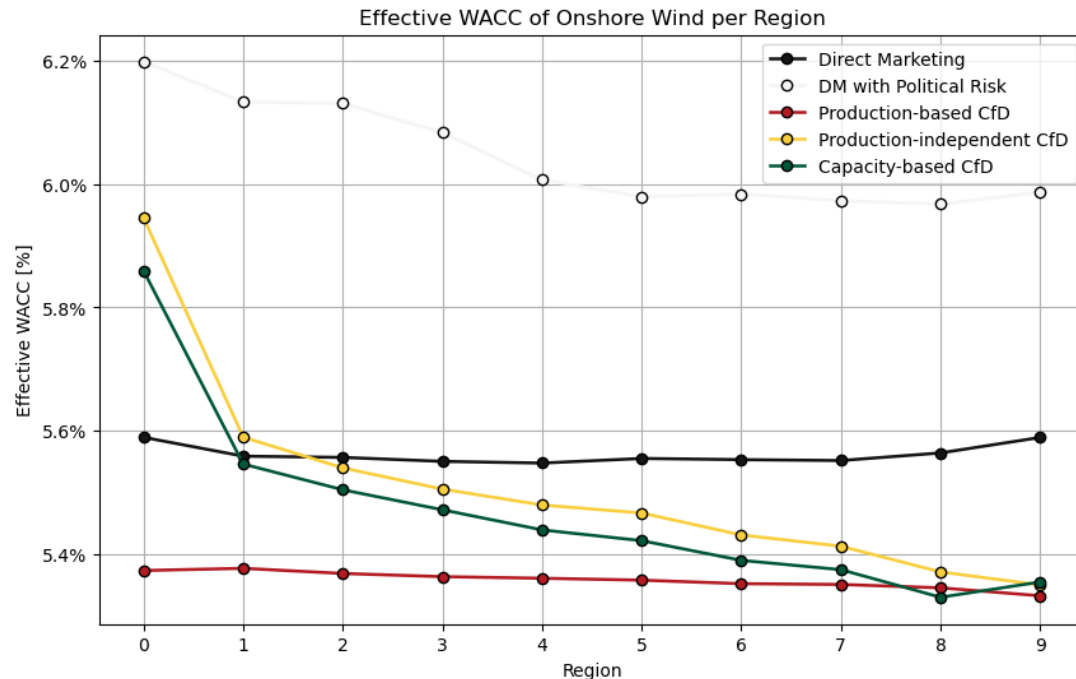
Cost of Capital Reduction through CfDs



Our findings suggest:

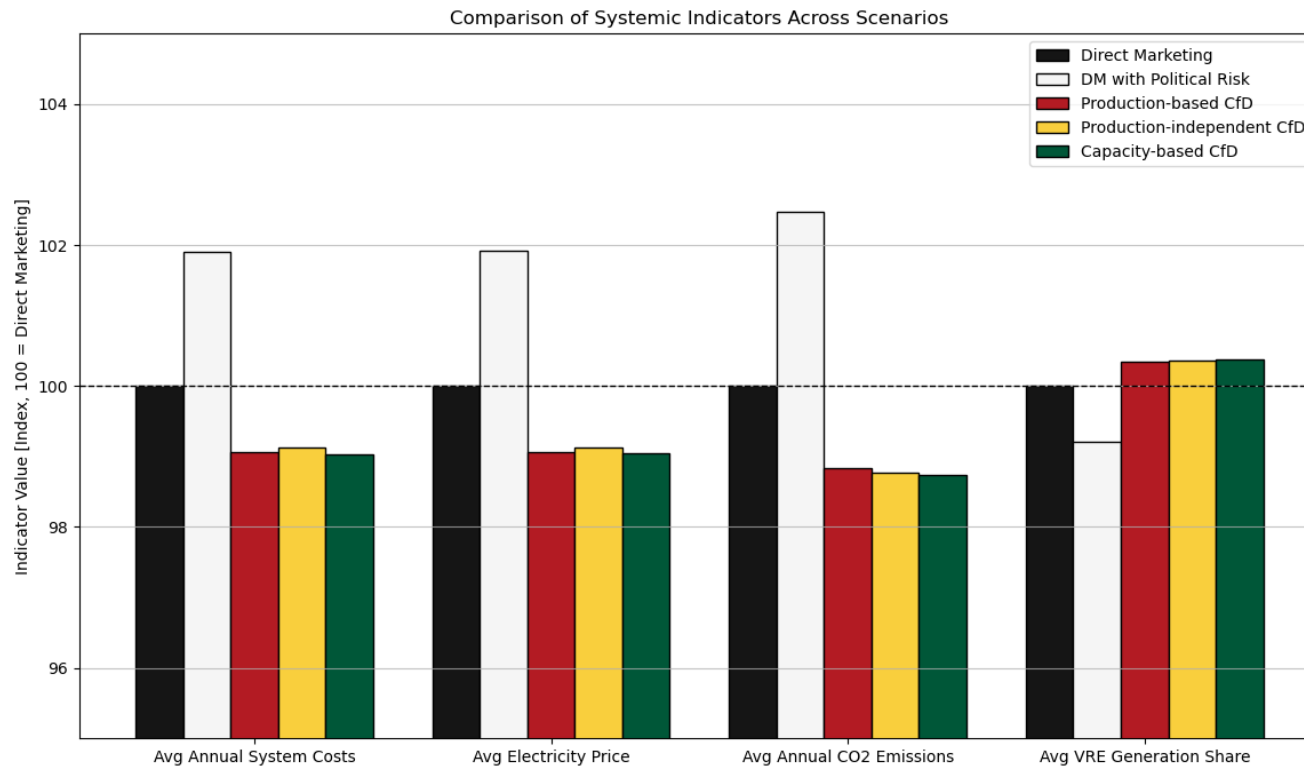
- CfDs more relevant as **hedge for political risks** than market risks
 - Insurance against market interventions
 - Independent of specific CfD design
- **No significant advantage of volume risk hedge** through capacity-based CfD
 - Largely averages out over entire contract duration
 - Only transfer of unpredictable long-term price risks with systemic effect

Risk Hedging Effectiveness across Regions



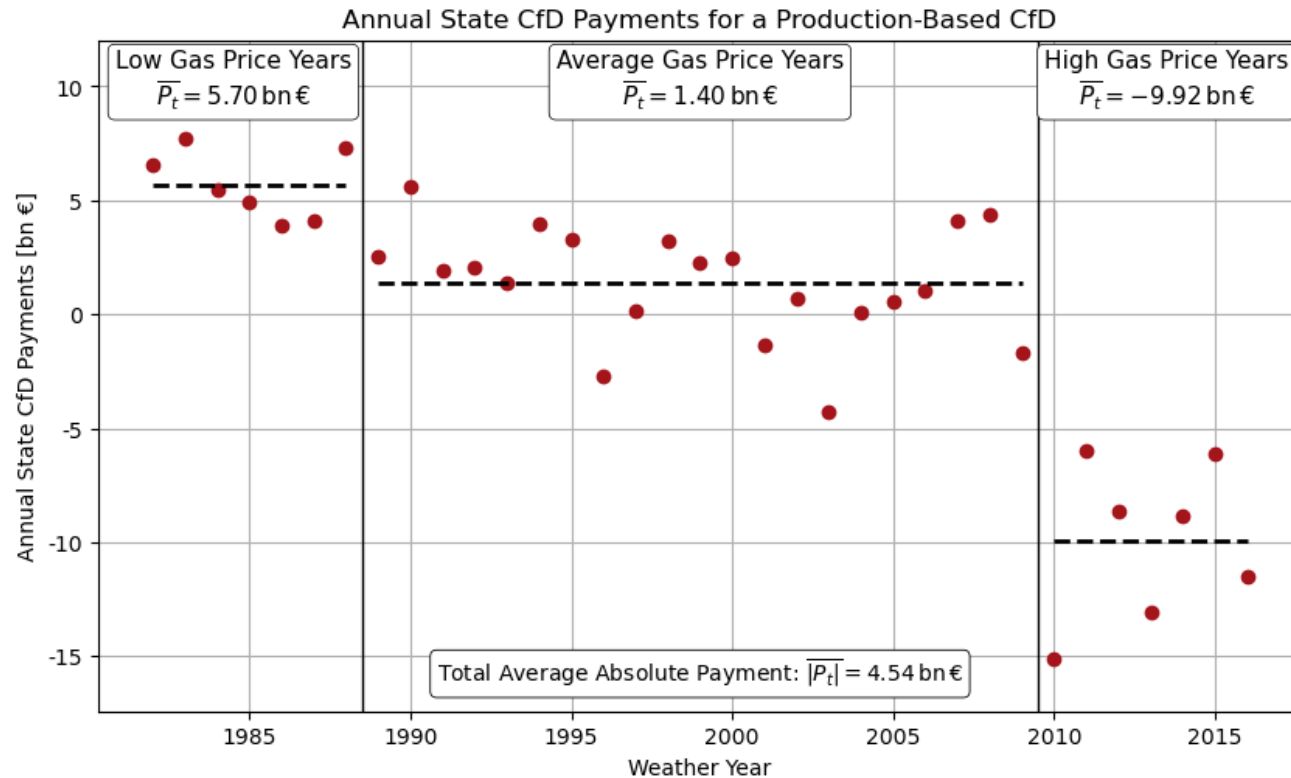
→ Significant basis risk for onshore wind for production-independent CfDs in regions where the production profile deviates from the reference profile (technology average across all regions)
 → **Misicentivizes investments to be less evenly distributed across regions**

Systemic Impact of CfDs



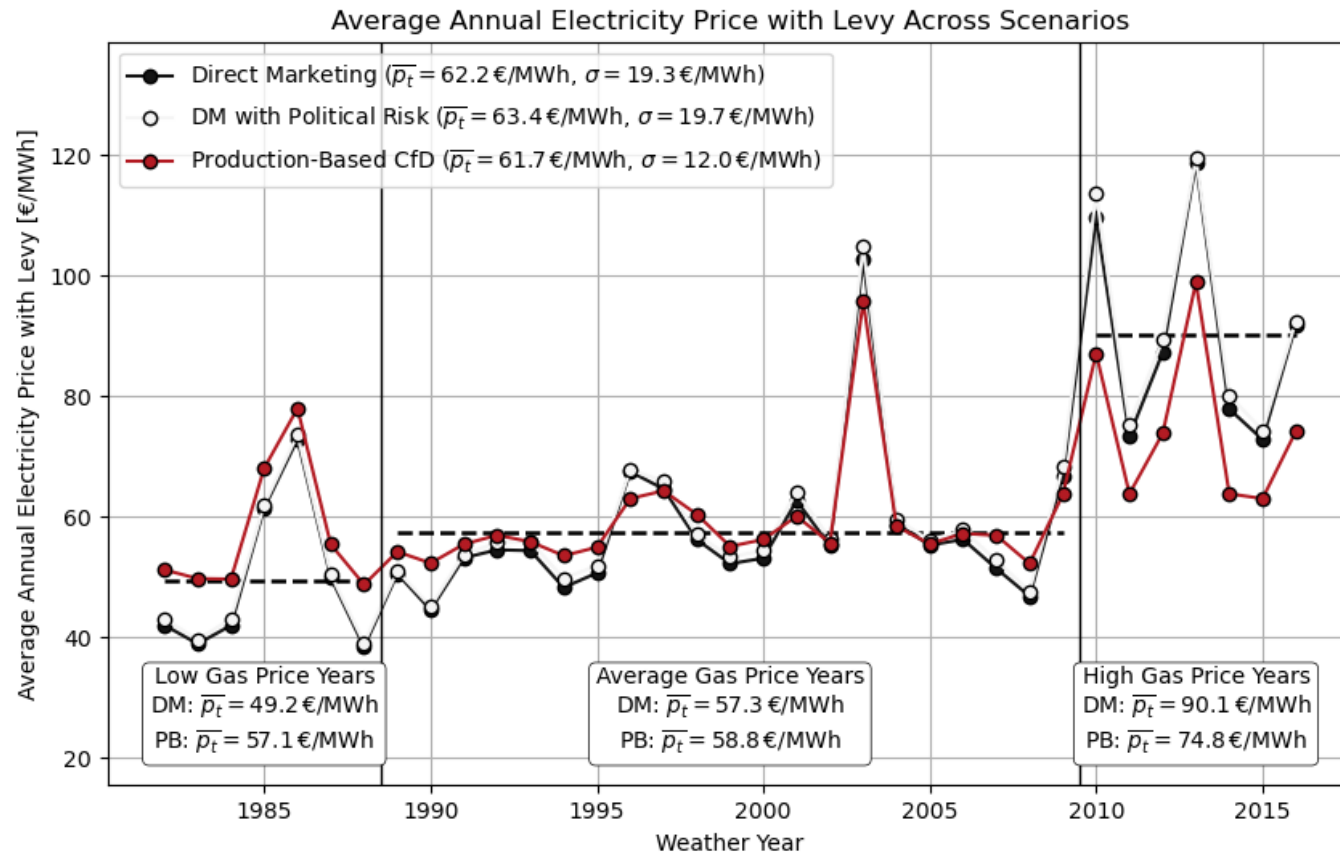
- **Reduction of electricity prices and system costs of ~0.9 / ~2.8 %**
 - Annual system cost reduction of ~0.4 / ~1.2 billion €
 - Average electricity price reduction of ~0.6 / ~1.8 €/MWh
- **Highest percentage decrease in annual CO2 emissions with ~1.2 / ~3.6 %**
 - Reduction of ~0.5 / ~1.5 Mt CO2 annually
 - Mainly due to reduction of full load hours of gas turbines

State Payments



- Net positive payments in “normal” years
- **Effective skimming of “excess revenue”** during high energy price years
- Expected absolute payments significantly higher than annual system cost reduction

The Impact of a Levying System



- Levy: direct transfer of CfD payments to consumers
- Reduces overall price fluctuations by a third
 - **Quite effective to buffer price hikes in energy price crises**
 - Smaller effect on weather-driven price variability
 - **Passing on price risks to consumers benefits both sides!**
 - More induced commodity demand as possible negative side effect
 - Contrary effect expected for demand shocks (i.e., during a recession)

Suggestions from our Paper

1. CfDs affect cost of capital, most importantly by hedging political risks
2. No meaningful difference in systemic impact between different CfD designs
3. System costs, consumer prices, and CO_2 emissions could be reduced by up to 3 %
4. Price risk transfer to consumers through levying system reduces their electricity price volatility
5. Production-independent CfDs can distort investment incentives between regions



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BACK-UP

Existing Approaches in the Literature

Assessments of the Impact of Policies on Cost of Capital for Assets on the Energy Market

Paper	Summary	Assumptions	Mechanism
Neuhoff et al. (2022) (doi.org/10.1016/j.reseneeco.2022.101330)	Analytical model that maximizes the debt share for a given revenue variability	<ul style="list-style-type: none"> • Cost of debt • Cost of equity • Annual returns for different policy instruments • Fixed Minimum share of equity (20 %) 	Only secured returns can be used for debt service CfDs → Higher secured returns → higher debt share → lower WACC
Đukan et al. (2025) (doi.org/10.1177/01956574251331942)	Numerical model that maximizes shareholder value by optimizing the debt share (via Monte Carlo simulation)	<ul style="list-style-type: none"> • Cost of debt • Cost of equity • Risk-free interest rate • Revenue variability • Debt service coverage ratio requirement 	Buffer between annual debt service and available cashflow correlated to default probability → increased cost of financial distress → reduced optimal debt share
Soysal (2025) (doi.org/10.1016/j.apenergy.2025.125425)	Iterative analytical model that optimizes the debt share with endogenous cost of debt	<ul style="list-style-type: none"> • Distribution of annual returns • Risk-free interest rate • Initial investment and terminal project value 	Expected return on debt equals return on risk-free investment for lender; Investor optimizes debt share for maximized return on equity
Lévêque et al. (2026) (doi.org/10.1016/j.rser.2025.116570)	CAPM-based empirical estimation of cost of capital and LCOE for different countries and policy schemes	<ul style="list-style-type: none"> • Risk-free interest rate • Risk premia for equity and debt • Country risks • VRE investment risks 	Monte Carlo simulation of cash flows and project returns, used to calculate default probability and project-specific risk premium for country-level WACC

Our Contribution

Research Gap:

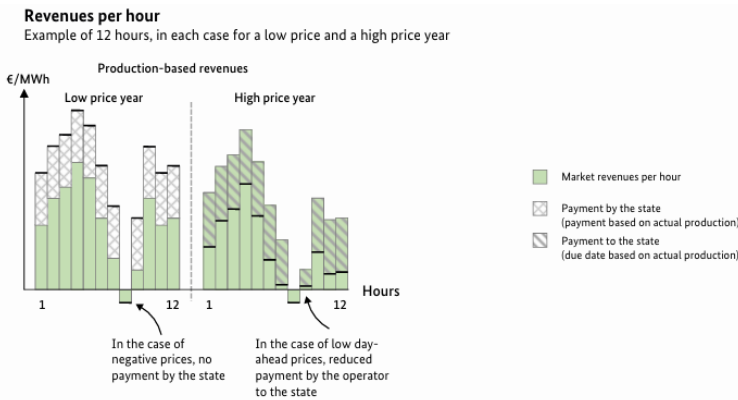
- **Integrated assessment** of impact of risk-hedging through CfDs on cost of capital and impact of cost of capital reduction on energy system
- **Quantification of systemic benefits** of private-to-public risk transfer
 - Increased optimal VRE market share
 - Reduction in average electricity prices
 - Reduction in GHG emissions
- Analysis of **impact of CfDs on state budgets** and public hedging options
- Discussion of **optimal revenue risk allocation** from systemic perspective

Our Approach:

1. Run greenfield **system-cost-optimization model** (*PyPSA-EUR* with 2030 cost and demand level assumptions & CO_2 price of 100 €/t) to generate revenue time series in long-term market equilibrium
2. Calculate **lifetime revenues and their risk** under direct marketing (with and without proxy for political risk) as well as under CfD schemes through Monte Carlo Simulation over annual revenues
3. Calculate **updated cost of capital** based on revenue risk under CfD schemes and use them as input for **new model iteration**
4. Compare **systemic indicators** for all scenarios
5. Assess impact on **volatility of state budgets** and impact of a levying system

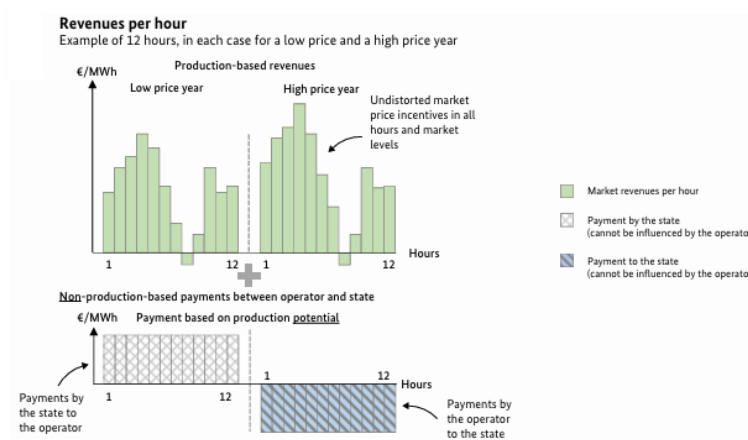
Contracts for Difference – An Overview

Conventional CfD



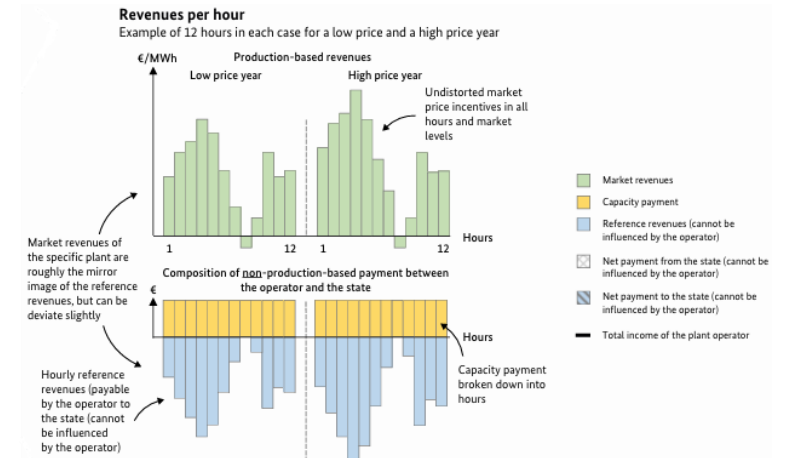
- Production-based CfD payments
- Only hedges **price risk**
- Imperfect incentives for system-friendliness
- Easier implementation

Financial CfD



- CfD payments based on virtual reference profile
- Only hedges **price risk**, introduces additional **basis risk**
- System-friendliness through full market signal

Financial CfD with capacity component



- Capacity payment to generator, clawback based on reference profile
- Hedges **price and volume risk**, **basis risk** remains
- System-friendliness through full market signal

Source: [BMWK options paper](#) (September 2024)

The Energy System Model

PyPSA-EUR

- Open-source configurable **system-cost-optimization model** of the European energy system
- **Co-optimizes grid capacities, generation and storage capacities & dispatch** over given weather years
- Generates hourly **nodal shadow prices** for all network nodes
- Interpretable as result of perfect electricity market

Our model configuration:

- Electricity-only model allowing all possible generator types
- German electricity price zone as single network node
- Greenfield model (“optimal rebuild” of electricity system)
- 10 regionalized types of VRE carriers representing regions with different generation potential quality
- Carbon price of 100 €/t CO_2

Input data:

- Investment & marginal costs for different generator types (default cost assumptions from PyPSA for 2030)
- VRE generation potentials for 35 historical weather years
- Synthetic 2030 demand time series for 35 weather years
- Value of Lost Load of 4000 €/MWh
- Endogenously calculated **cost of capital** (calibrated for direct marketing scenario through “zeroth” model run)

Control parameters:

- Natural gas price
- CfD designs via corresponding $WACC$ with strike prices set such that CfDs fulfill budget-neutrality
- Political risk proxied by price cap of 130 €/MWh

Lifetime Revenue Risks

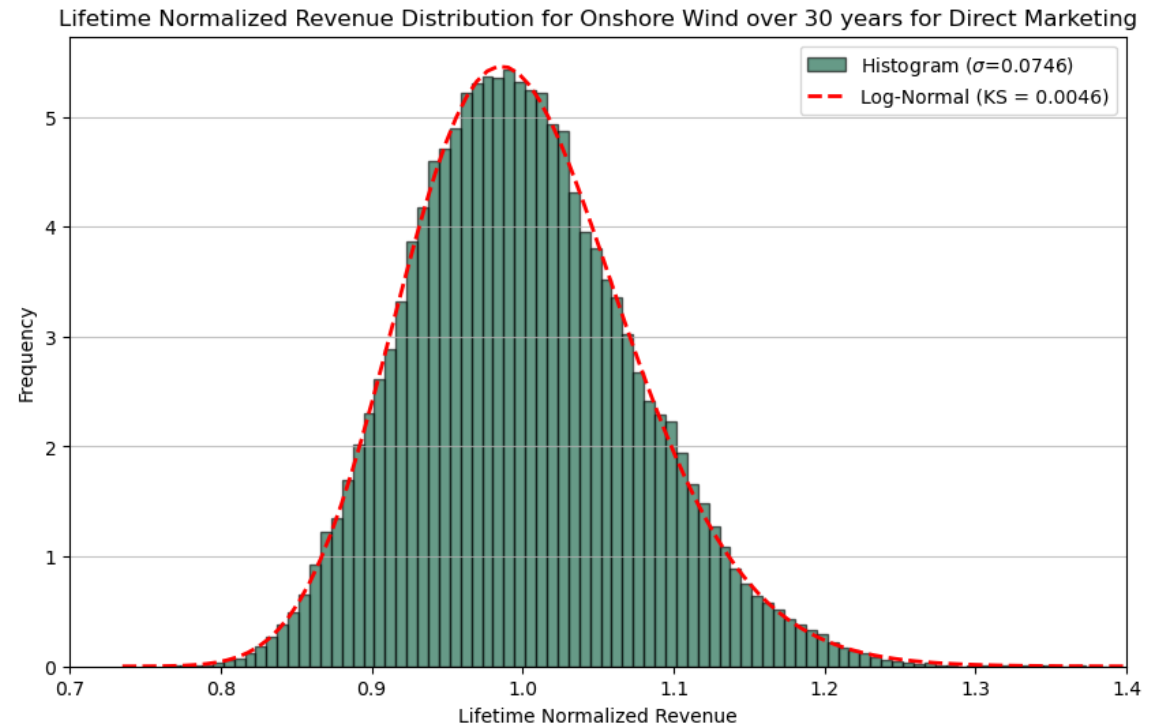
Two sources of risk in our energy system model:

- Uncertain production **volume** due to uncertain future weather, represented by 35 weather years
- Uncertain market **price** for produced electricity, represented by three levels of natural gas prices (assigned to fixed weather years)

Measure of risk: normalized **lifetime revenue variance**

$$\sigma_R^2 = \frac{1}{NR_T^2} \sum_{i=1}^T (R_{i,T} - \overline{R_T})^2$$

with lifetime T , lifetime returns R_T , and their average $\overline{R_T}$, estimated in Monte Carlo simulation ($N = 10.000$) randomly drawn from pool of 35 scenario years



Calculating Cost of Capital – Our Approach

Input:

- **Initial investment** I_0 per MW
- **Probability distribution for lifetime returns** R_T (log-normal) with observed expected returns $E[R_T]$ per MW & variance σ_R^2
 - Aggregated distribution of annual returns with same underlying probability distribution type
 - Allows calculation of default probability P_{def} for given interest rate
- Annual technology-specific **baseline interest rate** r_f
- Asset **lifetime** T : 30 years for wind, 40 years for PV
- Assume full payback of initial debt including interest at the end of the asset lifetime

Calculation (in terms of continuous compound growth rates):

- **Modigliani–Miller theorem**: independence of $WACC$ from debt & equity share (in perfect capital markets without taxes)

➤ Assume **uniform financing structure**

- **Merton Model**: Assume expected return on investment for lender equals return on risk-free investment (**zero-profit condition**) to calculate annual **weighted average cost of capital** $WACC$:

$$I_0 \exp(r_f T) \equiv E[ROI] = (1 - P_{\text{def}}) I_0 \exp(WACC \cdot T) + E[R_{\text{def}}]$$

➤ Essentially calculates and values tail risk

- For the **marginally viable investment** holds:

$$E[ROI] = \exp(WACC \cdot T)$$

➤ Under log-normal lifetime revenue distribution:

$$WACC = r_f + \frac{1}{T} \ln \left[\frac{1}{1 - \text{erf}(2^{-3/2} \sigma)} \right]$$

Calculating Cost of Capital – Our Approach

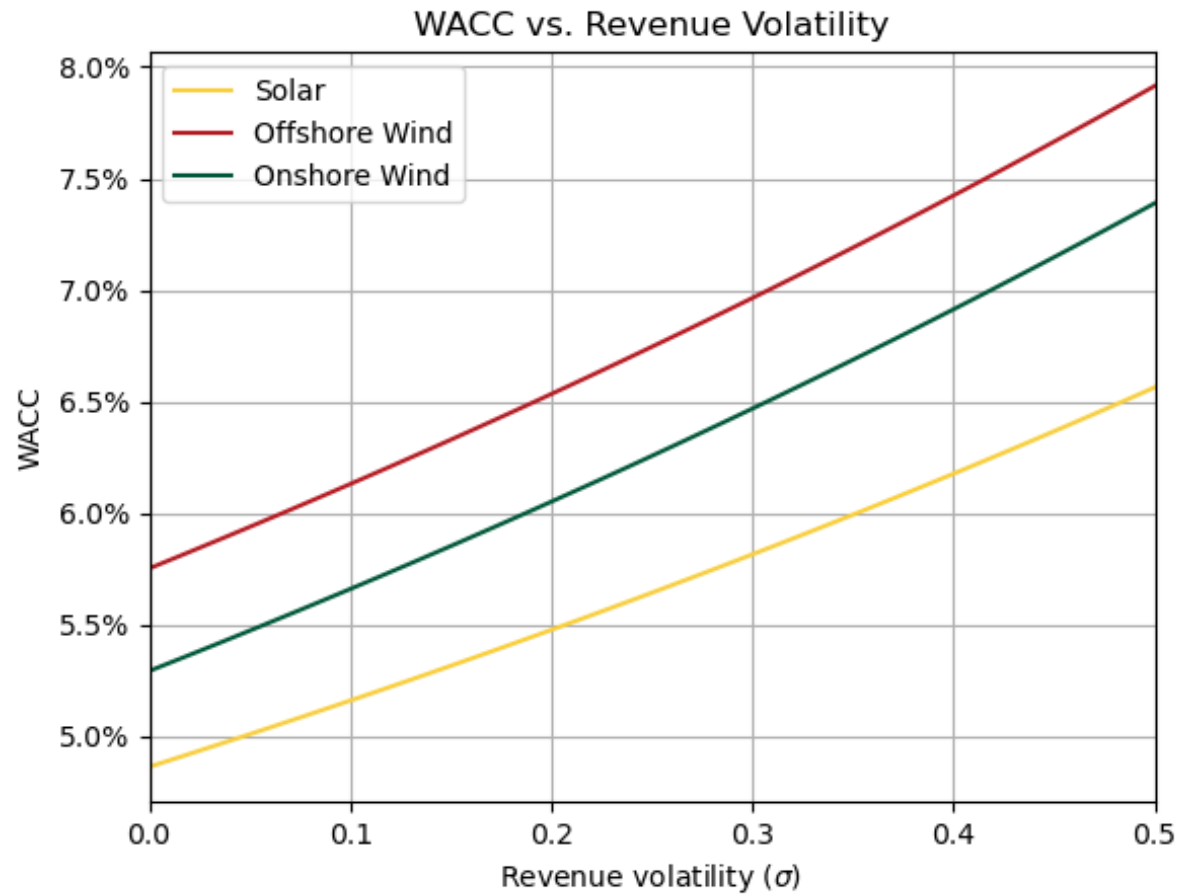
How to calculate the return distribution:

- **Sample of 35 annual revenues** for different weather years, 7 with low, 21 with average, and 7 with high natural gas prices
- Repeatedly (~10.000) draw **a number of years corresponding to asset lifetime** with replacement from available weather year realizations to **simulate distribution of lifetime returns**
- Fixed transition probabilities between **low, average, and high price years** such that each weather year has the same expected appearance rate and the average low/high price event lasts 2 years
- Calculate **risk** from aggregated Monte Carlo lifetime returns sample

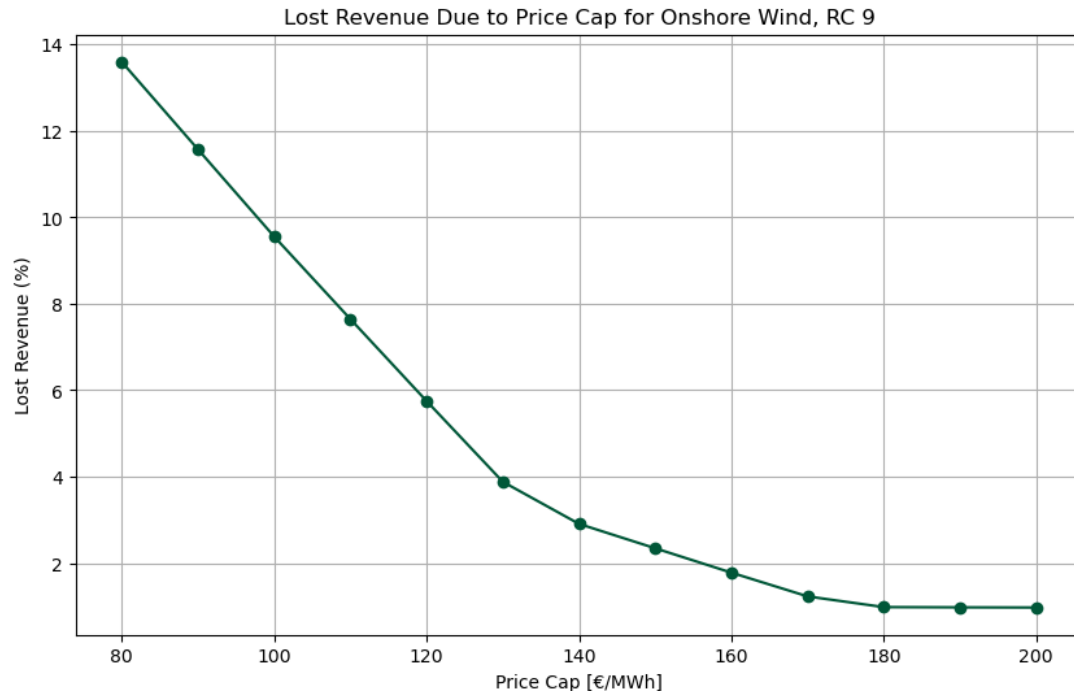
Limitations of the approach:

- Assumes external lender to be risk-neutral
- In reality, no equivalence of debt and equity & different financing structures for different projects depending on external factors
- Valuation of cost of debt typically based on empirical data, not on zero-profit condition
- Cost of equity very agent-dependent, varies between different companies, usually not generalizable
- Does not consider returns on an annual basis and thus default probability during the contract period
- Does not consider possible additional transaction costs for higher risk exposure
- Does not account for other sources of risk that the asset is exposed to over its lifetime (fluctuations in CO2 prices, energy carrier prices, or demand)

Calculating Cost of Capital – Our Approach

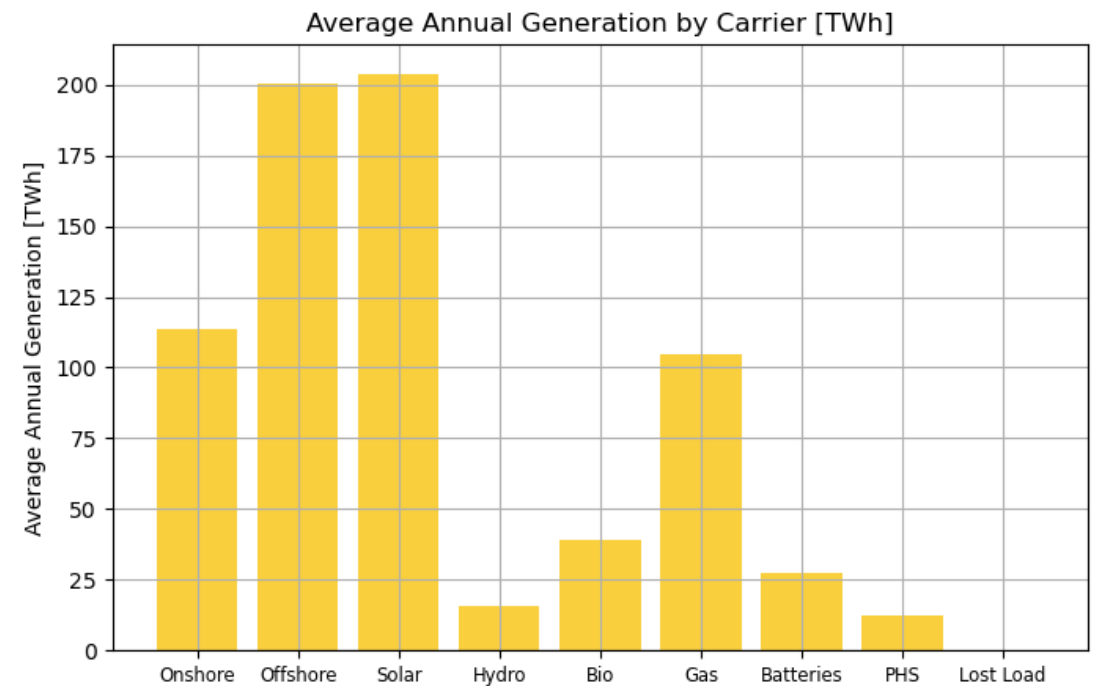
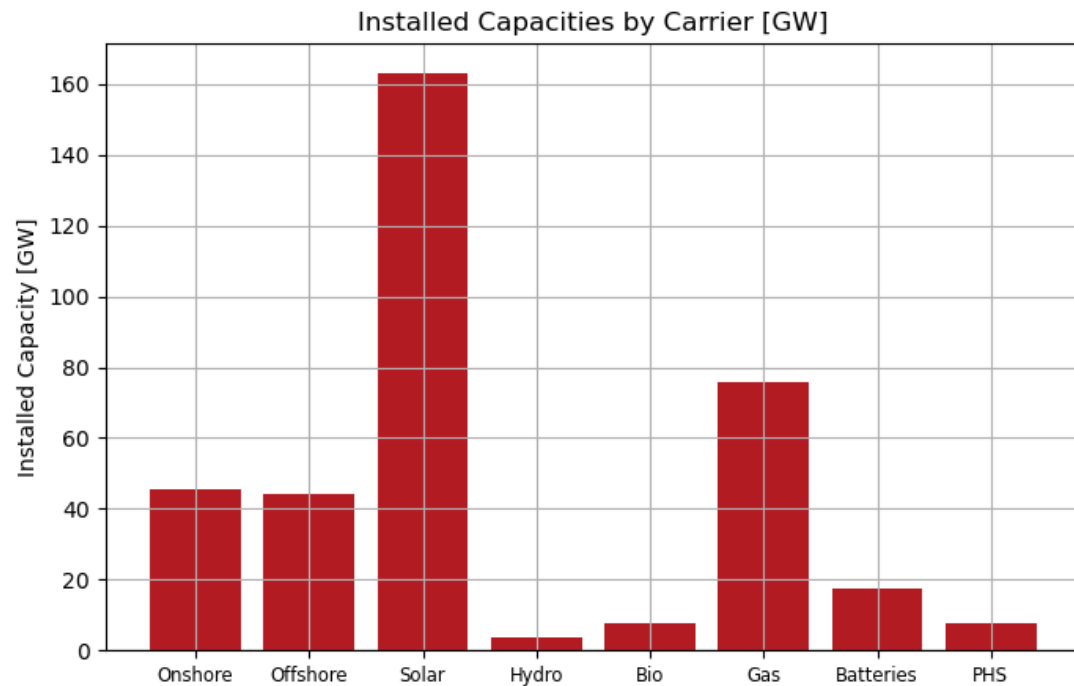


How to Quantify Political Risks?

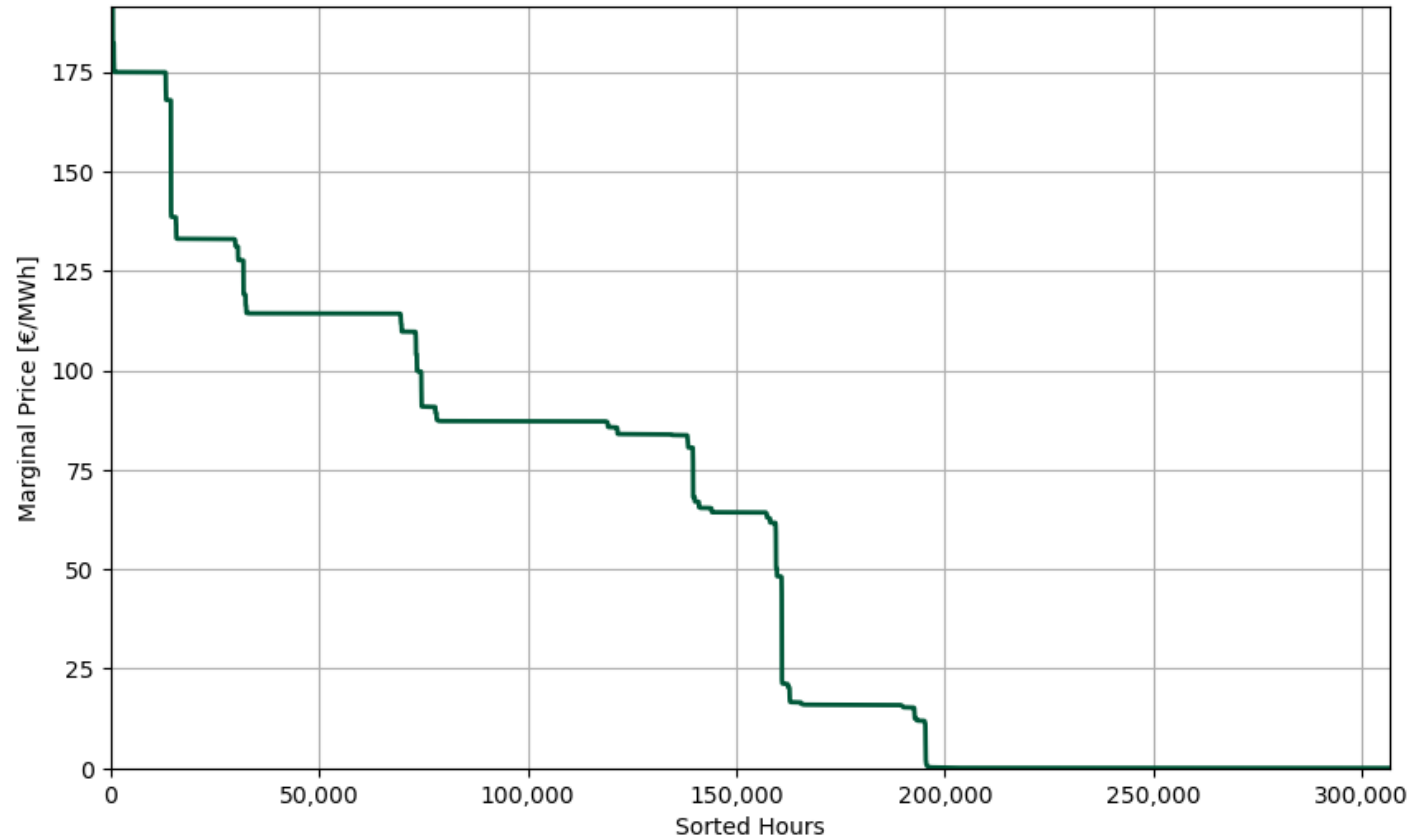


- Political risk fundamentally immeasurable
- Driven by trustworthiness of state institutions, mostly based on historical experiences
- We use a price cap of 130 €/MWh during high gas price years as a proxy to model political risk
 - Measures expectation of short-term intervention in energy crises as observed in the past through windfall taxes
- Translation into an effective higher WACC by calculating the effective no-cap ROI necessary to achieve the same ROI under a price cap as for the marginal investment in the direct-marketing scenario

Model Calibration – Capacities and Generation

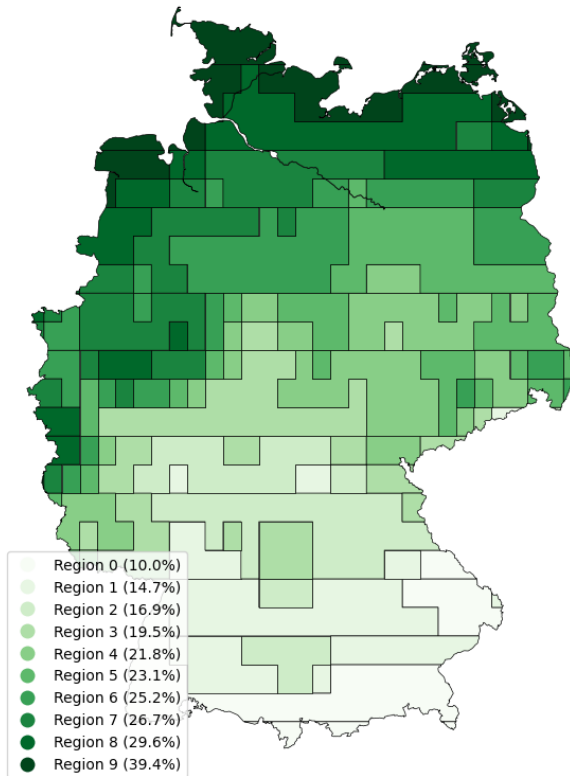


Model Calibration – Market Prices

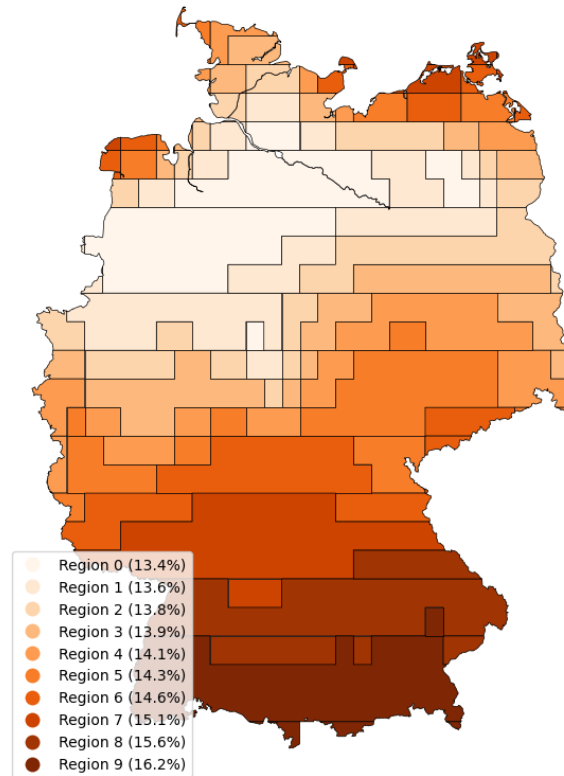


Model Calibration – Potential Regions

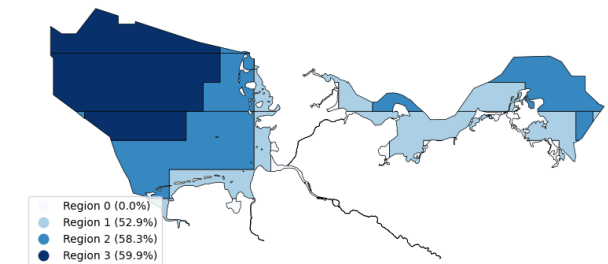
Potential Regions for Onshore Wind
(Average Capacity Factor in Parentheses)



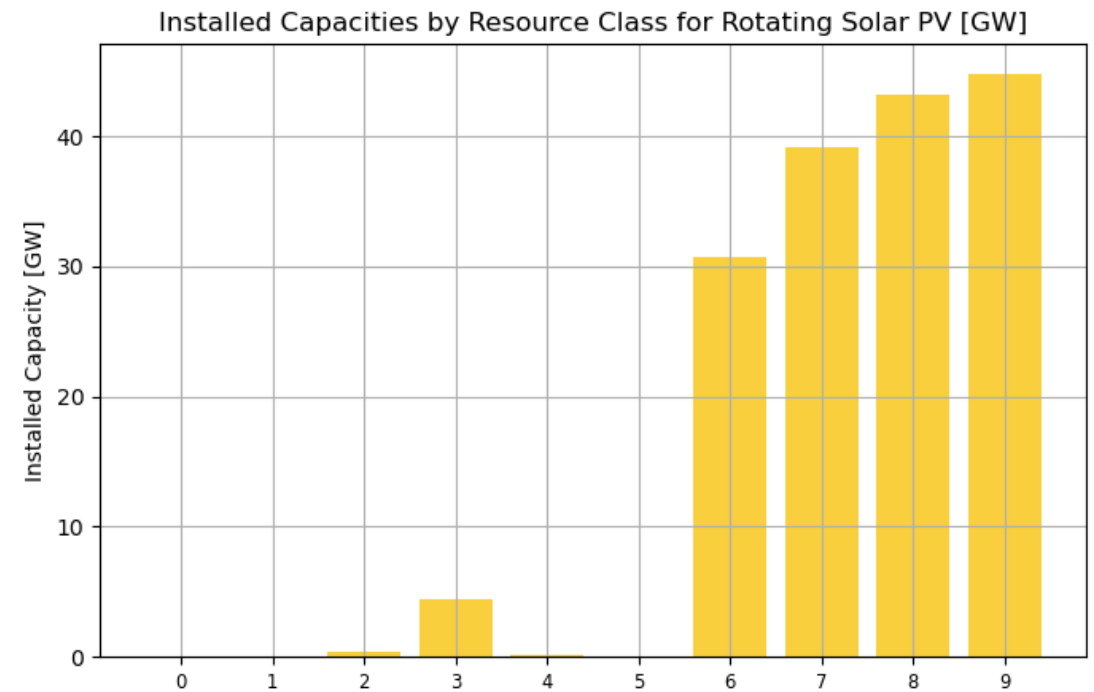
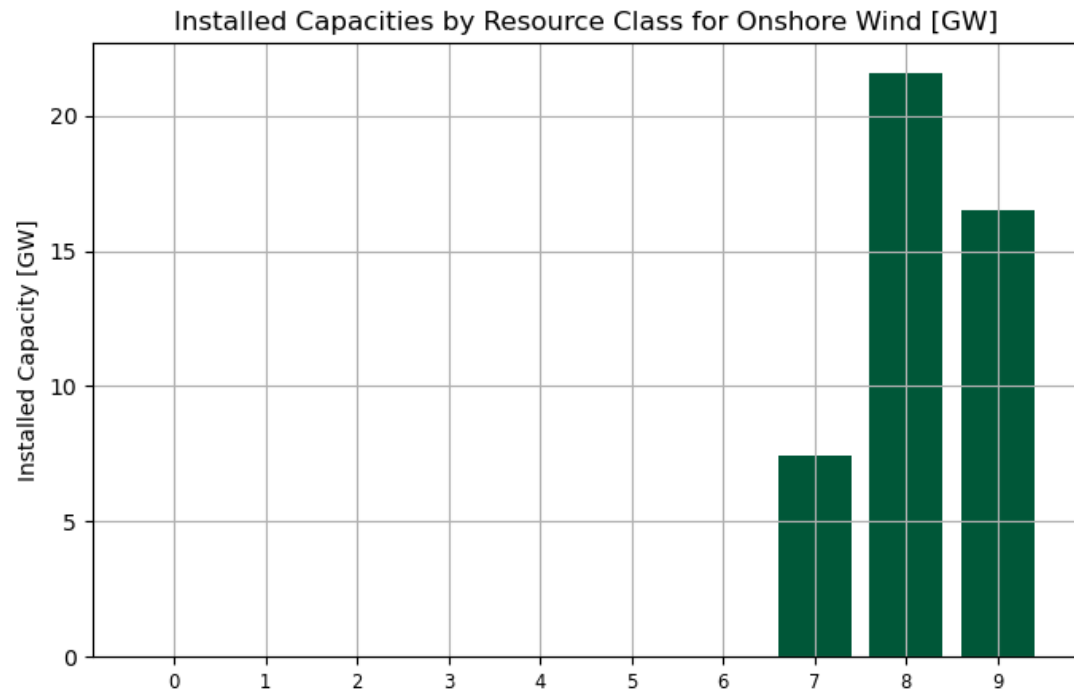
Potential Regions for Rotating Solar PV
(Average Capacity Factor in Parentheses)



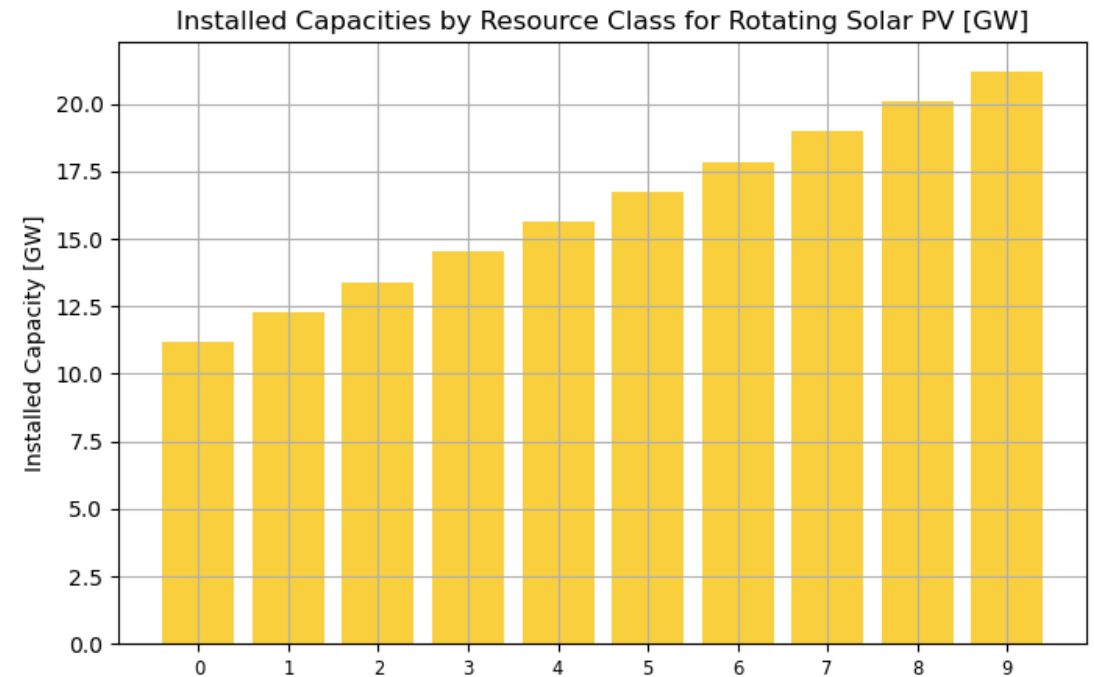
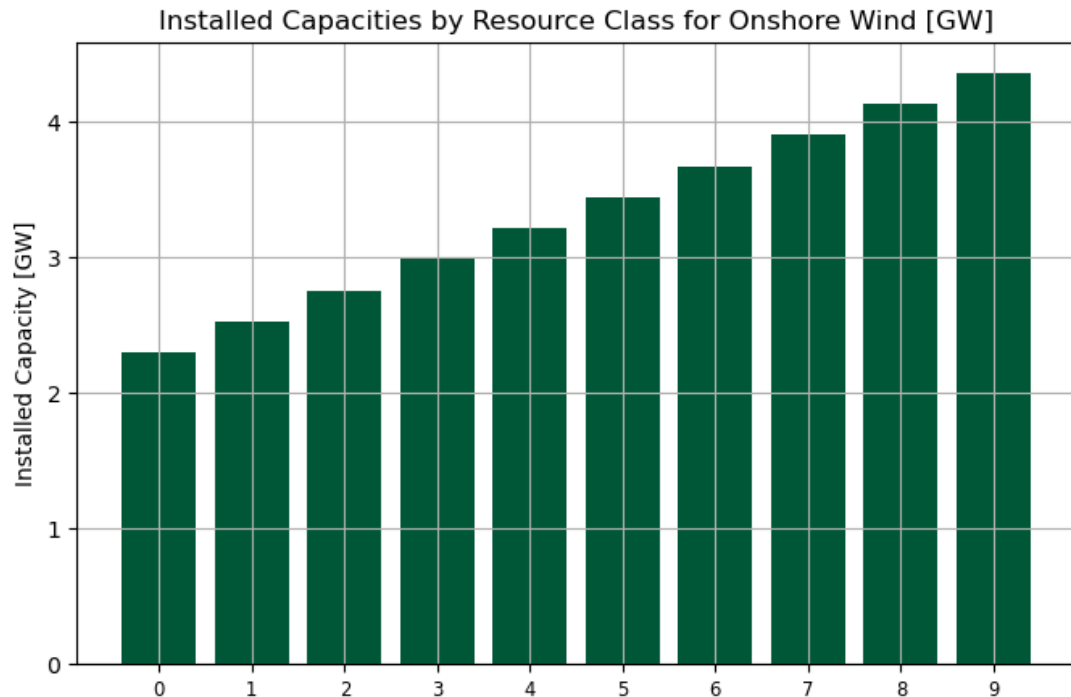
Potential Regions for Offshore Wind (DC)
(Average Capacity Factor in Parentheses)

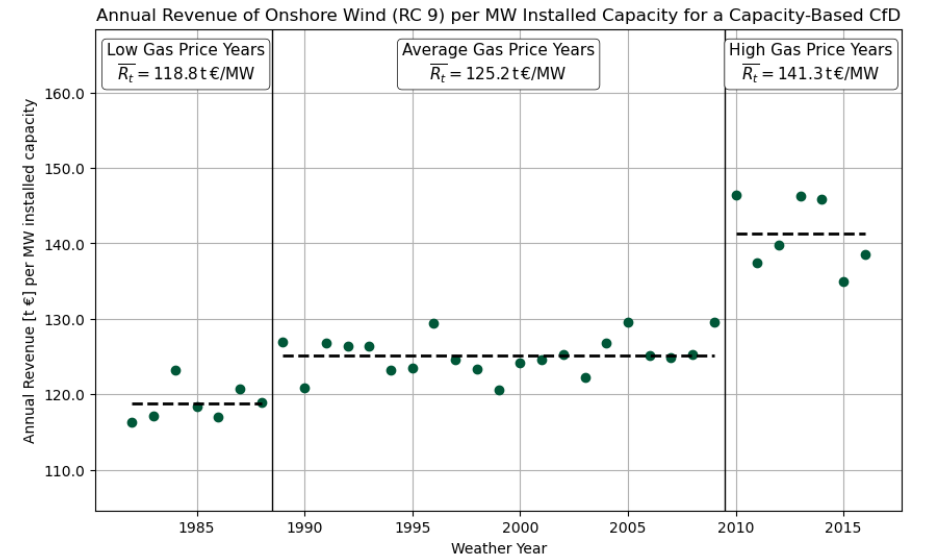
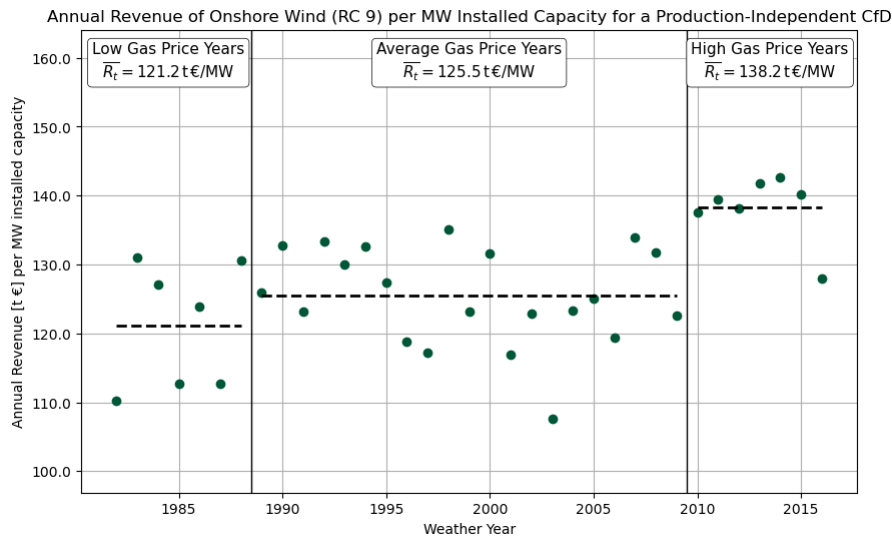
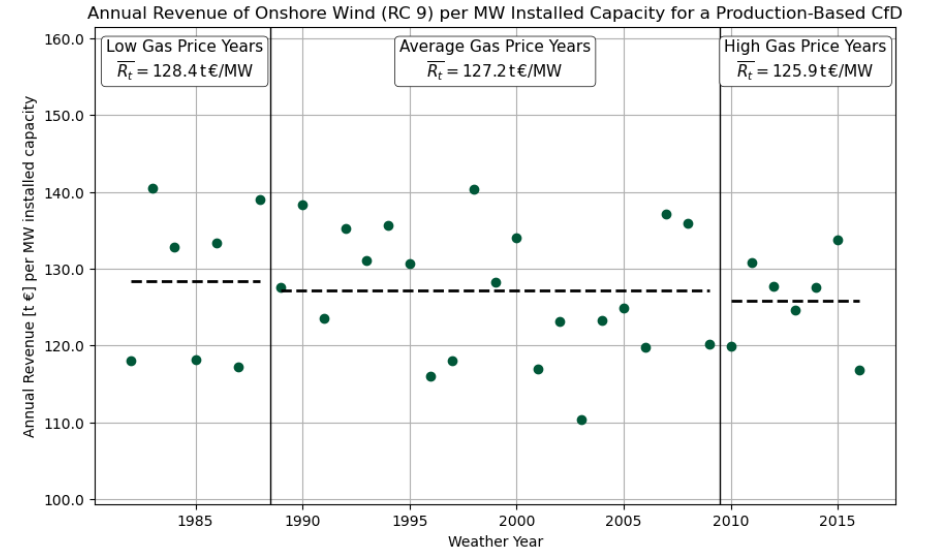
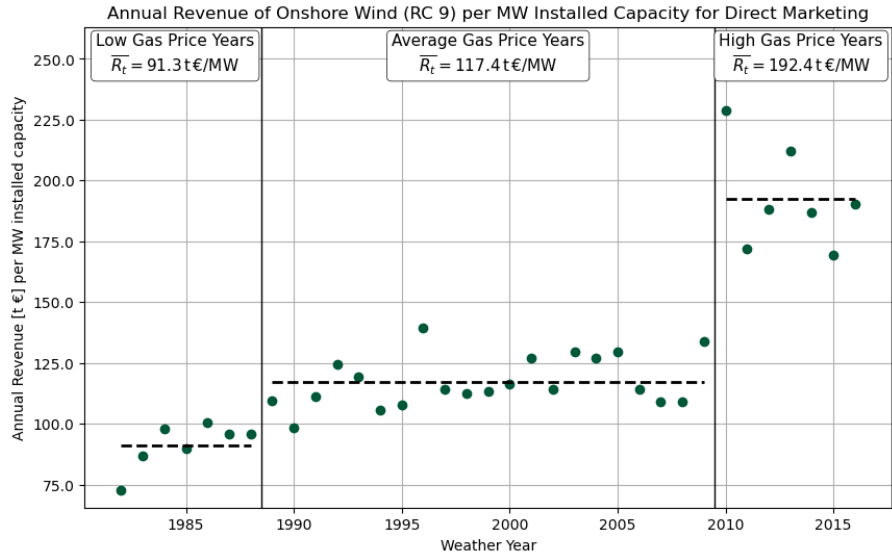


Model Calibration – Potential Regions



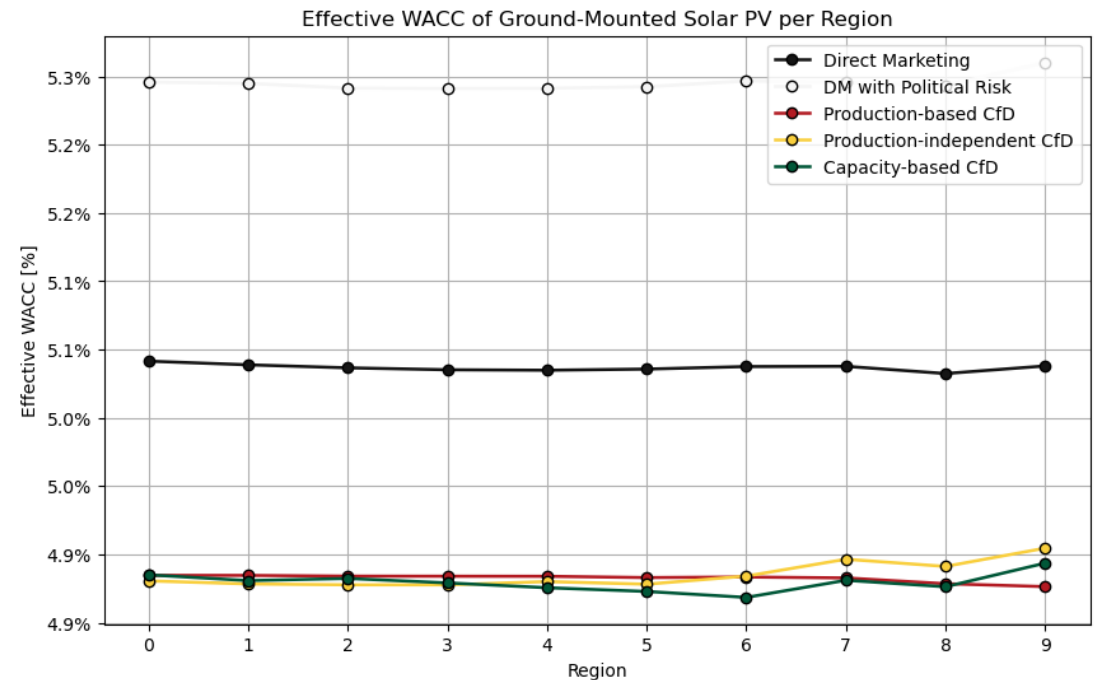
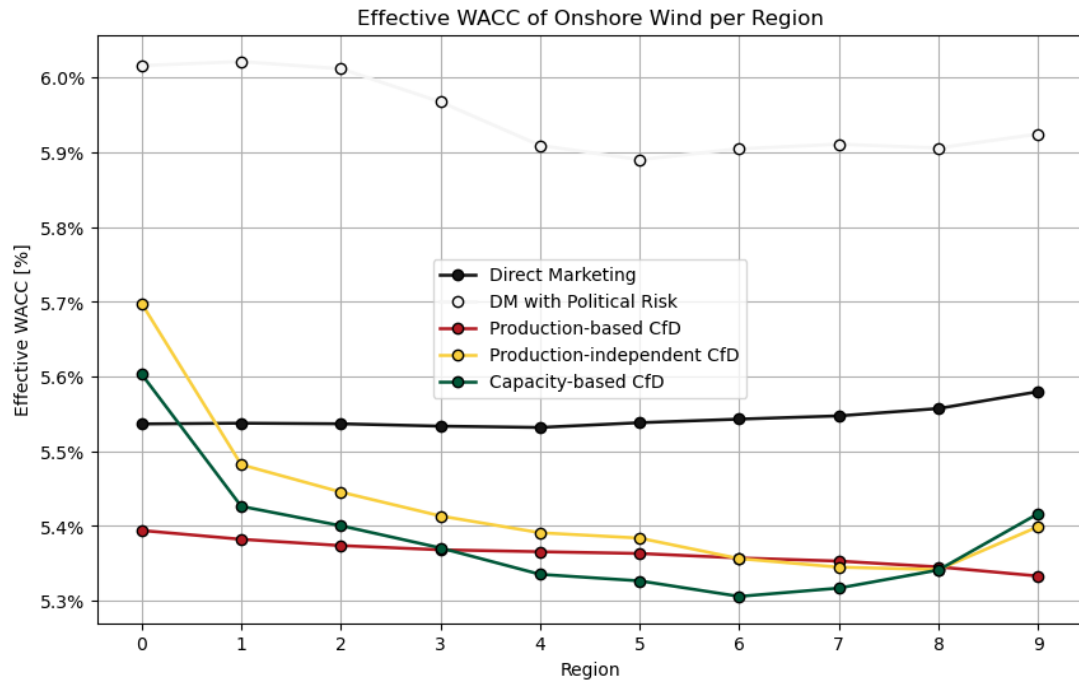
Model Calibration – Potential Regions (Fixed Constraints) (Sensitivity Run)



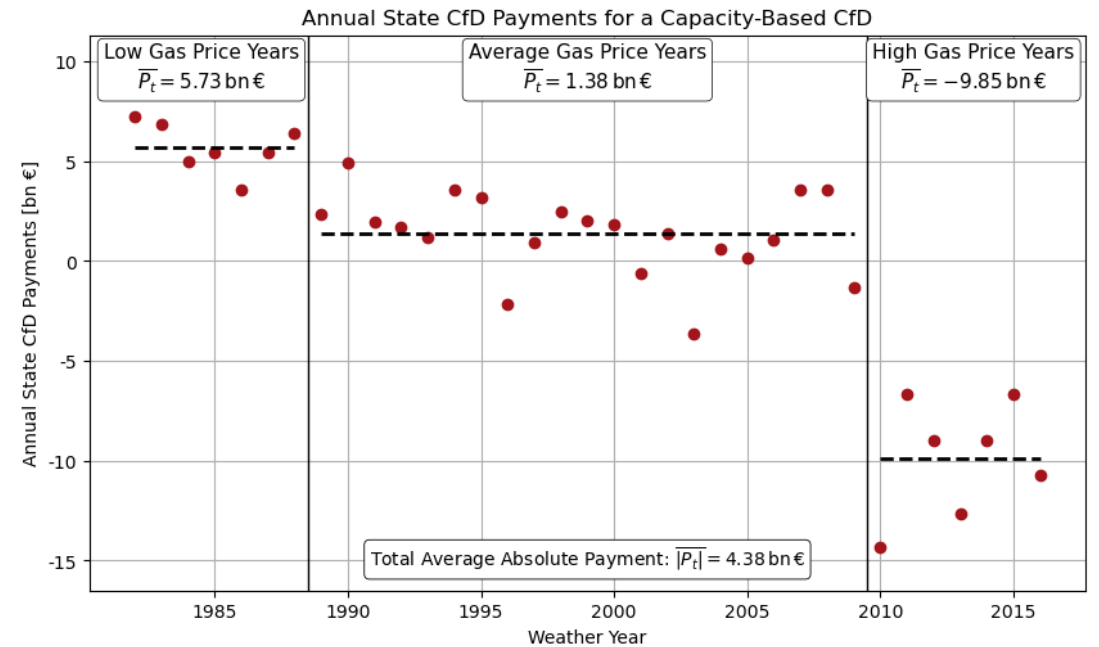
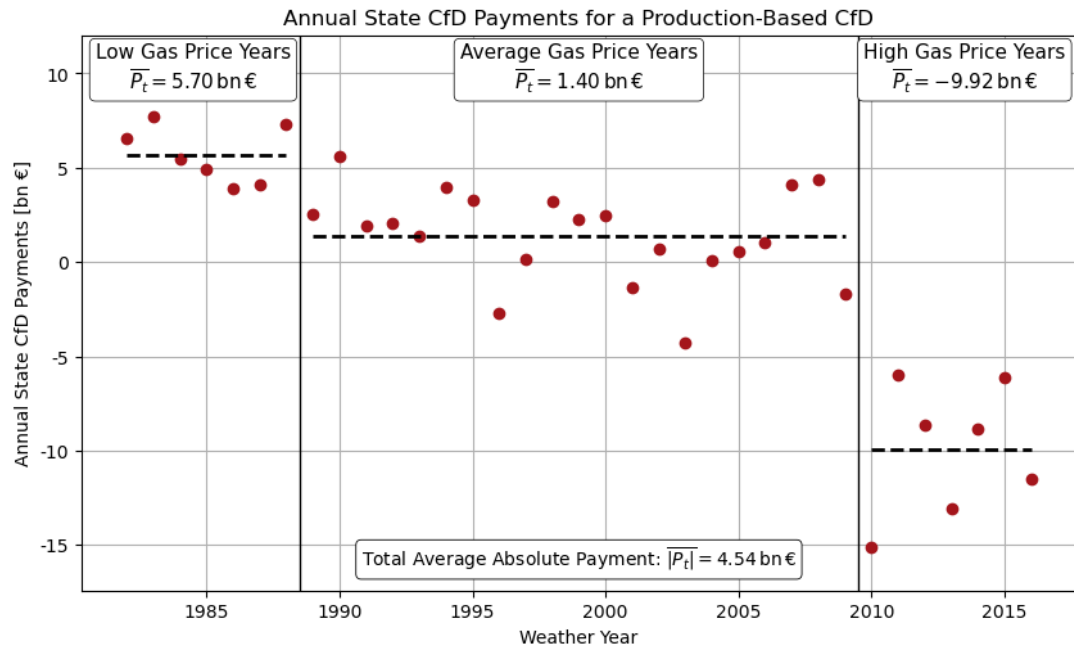


Risk Hedging across Regions (Fixed Constraints)

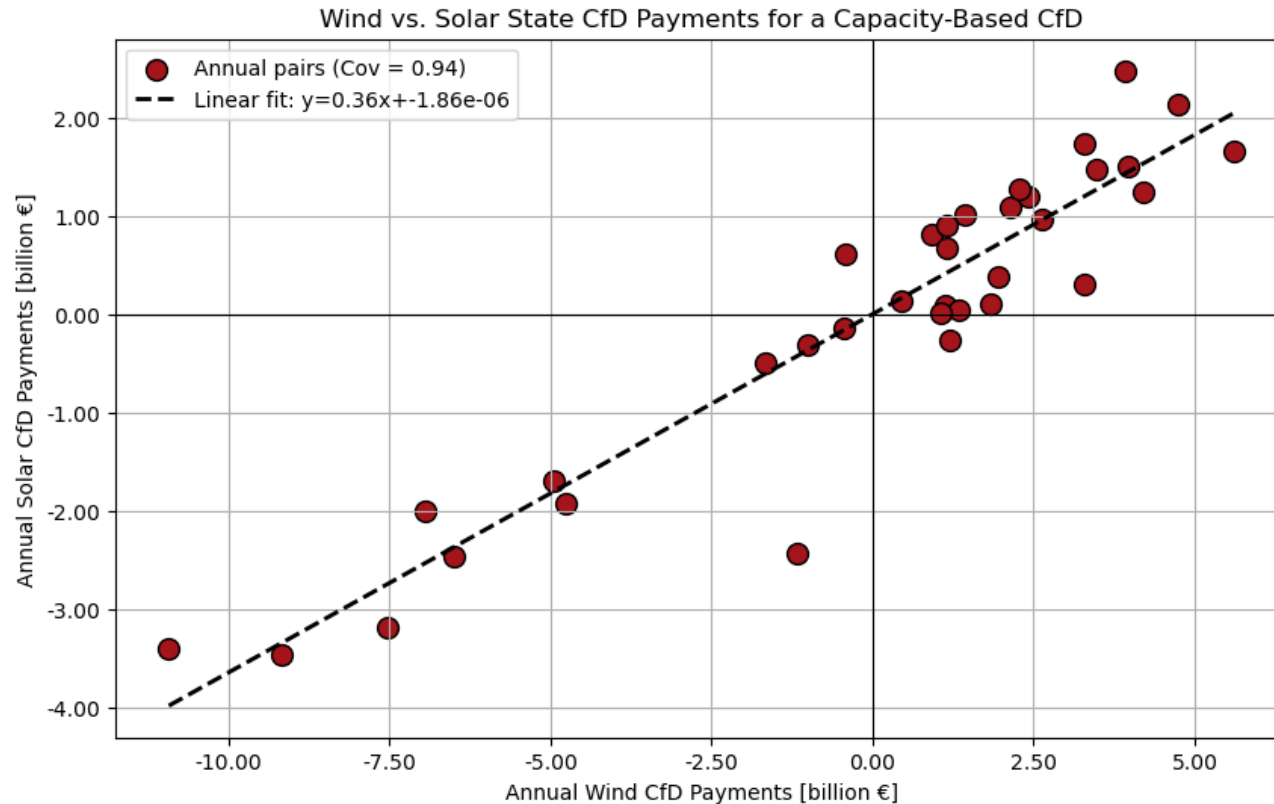
(Sensitivity Run)



State Payments for different CfD Types

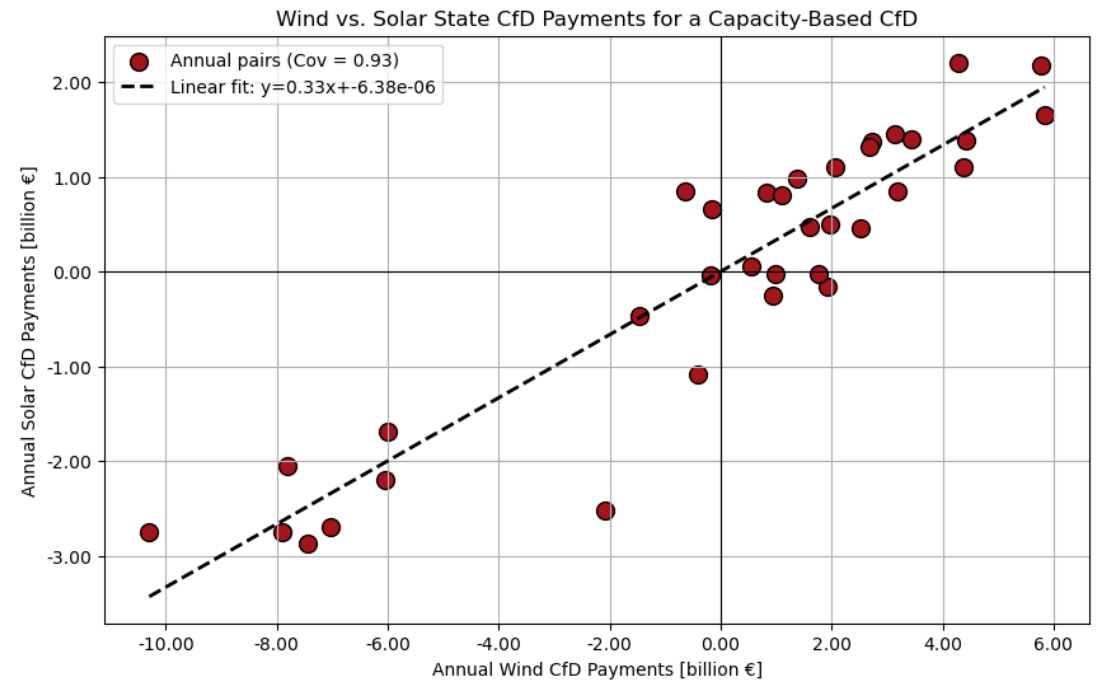
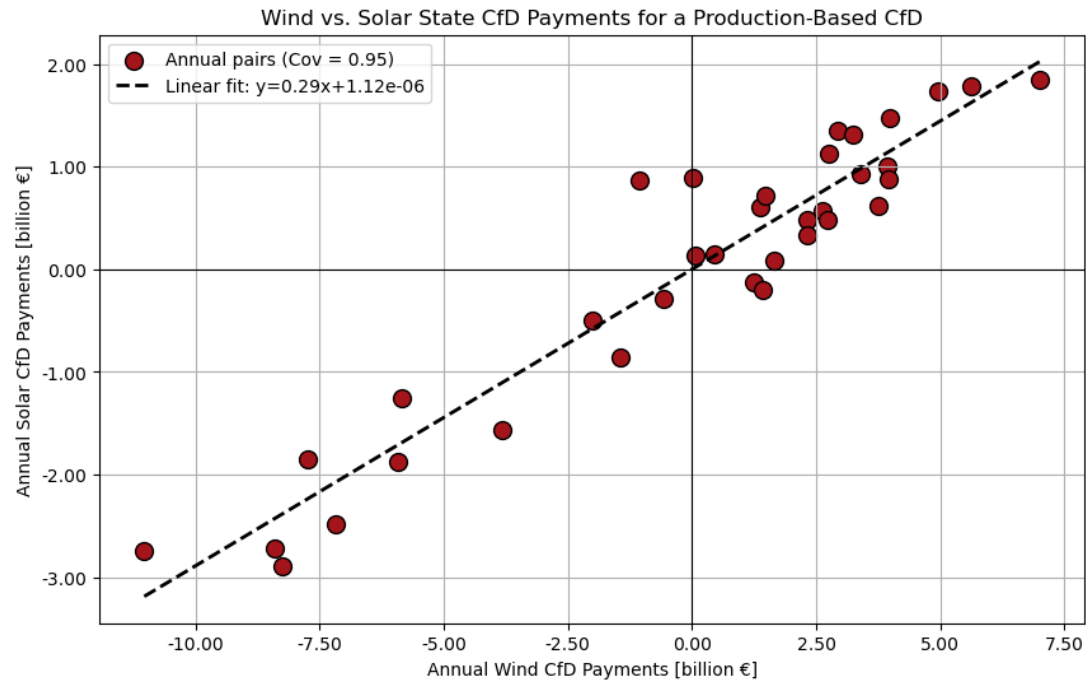


Size of the Portfolio Effect



- Wind is subject to ~3 times the payments, even though it only makes up ~1.5 times the generation compared to solar
 - CfDs for solar “cheaper” for the state
- Very high correlation between annual payments to wind & solar generators
 - Even for CfD that hedges weather risks
 - Mainly driven by correlated price risks
 - Underscores minor role of weather risks
 - **“Portfolio effect” almost insignificant**

Portfolio Effect



Outlook

Interesting further research:

- Consideration of price uncertainty induced by **demand level fluctuations** (linked to overall economic activity) as well as **changes in the market structure**
- Structural **theoretical dissemination of system-optimal allocation of risks** incurred throughout the energy transition as well as of other suitable hedging instruments for states
- **Comparative analysis of similar state-sponsored risk-hedging instruments** like PPA guarantees or capacity markets

Limitations of the model:

- **Exaggerated impact of CfDs** due to assumption of full market coverage
- **No consideration of investment cycles & ongoing transition process**, assumes the system to be in a long-term market equilibrium
- Possible **structural underestimation of price volatility** in electricity market models (e.g., no reproduction of negative price hours)
- Does not consider **costs of transmission capacity**, especially additional costs for CfD scenarios
- No consideration of **strategic auction bidding behavior** which introduce a subsidy component to CfDs
- No consideration of various **investment- and dispatch-distorting incentives** under CfDs
- No consideration of **interactions with other bidding zones**