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EWI Working Paper, No 25/10

November 2025

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ISSN: 1862-3808

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Optimal bidding of uncertain renewable electricity in sequential markets - Implications of risk aversion and imperfect competition

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Abstract

This paper develops an analytical model of sequential electricity markets in which renewable and conventional producers compete in two stages. Building on previous work, we introduce risk-averse renewable producers and distinguish between competitive and oligopolistic renewable producers. The model captures strategic bidding behavior under uncertainty in renewable production and limited flexibility of conventional producers in the second stage. Our results show that risk aversion amplifies strategic withholding in oligopolistic settings, thereby increasing the forward premium. This effect intensifies when conventional producers are less flexible. While risk aversion has no impact on welfare under perfect competition or when conventional producers are fully flexible, its interaction with market power and supply-side inflexibility generates welfare losses. In a heterogeneous market structure of renewable producers, competitive producers benefit from higher prices caused by the withholding of oligopolistic producers, particularly when those producers are risk-averse.

Keywords: Sequential Markets, Strategic Bidding, Risk Aversion, Market Power, Renewable Energy

JEL classification: D43, D81, L13, L94, Q21

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1. Introduction

Electricity markets balance supply and demand through sequential markets. These involve a day-ahead market for forward scheduling, followed by intraday and balancing markets. Positions taken in the day-ahead market can be adjusted in the intraday market, which allows continuous trading close to delivery (EPEX SPOT SE 2025). The intraday market plays an increasingly important role in absorbing fluctuations of variable renewable energy sources (RES), as the share of RES increases. In principle, sequential trading allows market participants to incorporate updated information over time, improving efficiency under uncertainty (Ito and Reguant 2016). However, it also creates strategic opportunities. For example, a renewable energy (RE) producer expecting a certain output may bid conservatively in the day-ahead market, then increase quantities in the intraday market if forecasts improve to abate high balancing costs. Economic theory predicts that, in frictionless settings, prices across stages should converge in expectation. Yet, empirical studies show systematic price differences between the day-ahead and intraday market, so-called forward premia, which can emerge from the use of market power (Ito and Reguant 2016; Borenstein et al. 2008; Saravia 2003). Besides market power, another explanation for the emergence of forward premia could be the risk perception of RE producers influencing bidding behavior on the day-ahead market (Botterud et al. 2010).

While existing research has studied forward premia and strategic bidding, these analyses often rely on simplified assumptions about risk preferences and market structure (Allaz 1992; Ito and Reguant 2016). We address this gap by analyzing how risk aversion, the degree of flexibility among conventional producers, and heterogeneity among RE producer jointly influence bidding behavior of RE producers in sequential electricity markets. We develop a stylized analytical model of competition between RE and conventional producers in two sequential stages. The first stage represents the day-ahead market, where producers submit bids before actual renewable output is known. The second stage corresponds to the intraday market, where uncertainty is resolved and producers can adjust their positions based on realized generation. Our findings show that risk-averse RE producers in an oligopolistic setting withhold more than risk-neutral producers in the first stage, which increases forward premia. The premium rises with the degree of risk aversion, especially when demand is sufficiently high relative to expected RE production and when conventional supply is inflexible. Limited flexibility among conventional producers amplifies the welfare losses associated with risk-averse behavior. Finally, we demonstrate that fringe producers can benefit from the market power exerted by risk-averse oligopolists, reshaping the distribution of rents.

This paper contributes to the literature on strategic bidding in sequential electricity markets by focusing on the interaction between risk aversion, uncertainty in RE generation, and market power. A first line of research studies forward contracting and strategic behavior in sequential markets. The foundational work by Allaz and Vila (1993) shows that firms can use forward contracts to commit output strategically, thereby mitigating market power and promoting more competitive outcomes in subsequent spot markets. Building on this, Ito and Reguant (2016) develop a two-stage model showing that market power and limited arbitrage can jointly generate systematic forward premia. Using microdata from the Iberian market, they find that dominant firms withhold in the day-ahead market, while fringe producers exploit price differences. They show that enabling full arbitrage reduces consumer prices but may not improve welfare if market power persists in intraday market. A similar contribution by Knaut and Obermüller (2016) shows that withholding by RE producers declines with increasing competition and disappears under perfect competition. The model further illustrates that the steepness of the intraday supply curve reduces withholding, and that welfare losses arise primarily when the steepness is high relative to the steepness in the day-ahead market, and when the renewable sector is concentrated. Obermüller (2017) shows that weather-related uncertainty drives withholding, and thus, forward premia in the German market. However, the aforementioned studies do not consider risk aversion. Crampes and Renault (2021) address this by showing that risk aversion and supply inflexibility jointly shape forward premia, with forward contracting and operational flexibility acting as substitutes in managing demand risk. Limited flexibility, in turn, constrains efficient risk sharing and amplifies welfare losses. Beyond theoretical models, a number of empirical studies confirm that forward premia in electricity markets are often driven by strategic behavior and market power. Borenstein et al. (2008) show that observed premia in California cannot be fully attributed to estimation errors or transaction costs. Instead, their findings point to market power as a likely explanation. Similar results have been reported for other electricity markets: Longstaff and Wang (2004) find persistent forward premia in the Pennsylvania-New Jersey-Maryland (PJM) market, Hadsell (2008) document systematic price differentials between day-ahead and real-time prices in New England, and Bowden et al. (2009) report similar patterns for the Midwestern United States wholesale electricity market. While the above literature focuses on strategic interactions in sequential markets and the role of market power, a complementary strand emphasizes risk-related explanations for forward premia in electricity markets. Bessembinder and Lemmon (2002) develop a general equilibrium model showing that forward premia in electricity markets emerge from the net hedging pressure of risk-averse market participants under demand uncertainty. Retailers, seeking to insure against high spot prices, tend to take long forward positions, whereas producers, aiming to protect against low spot prices, take short positions. The resulting net hedging pressure determines both the sign and magnitude of the premium, with its absolute value increasing in demand volatility and the convexity of production costs. Under perfect competition or risk neutrality, the premium vanishes. Schwenen and Neuhoff (2024) find that stronger negative covariance between renewable output and spot prices reduces hedging needs of conventional generators and increases forward premia. Bunn and Chen (2013) investigate drivers of forward premia in the British market and show that they are driven more by behavioral factors such as reaction to past premia rather than fundamental factors.

Our analysis is based on the research approach and the findings of Ito and Reguant (2016) and Knaut and Obermüller (2016). We contribute to the literature in three key ways. First, we extend the theoretical model by explicitly incorporating risk aversion into the bidding rationale of RE producers. Second, we analyze how risk-averse RE producers adjust their bids in response to differences in the flexibility of conventional producers. Third, we introduce heterogeneity among RE producers, allowing for both fringe and risk-averse oligopolistic RE producers. In particular, we quantify impacts on bids, price differentials, rent distributions, and overall welfare.

2. Analytical model

In this section we develop a stylized two-stage model of sequential electricity markets in which RE producers with uncertain output and conventional producers trade electricity. The first stage is associated with trading in the day-ahead market, while the second stage corresponds to the intraday market. The framework builds directly on the approach of Ito and Reguant (2016) and Knaut and Obermüller (2016), extending it by incorporating risk-averse bidding behavior and altering the composition of RE producers.

2.1. Model Setup

We consider a market in which N RE producers submit bids in the first stage and adjust their positions in a subsequent second stage where the uncertainty is resolved. The demand side is modeled as deterministic and perfectly inelastic with total demand d. Conventional producers act as perfectly competitive and have positive marginal costs. Together they form a linear marginal cost curve:

$$MC(q) = a \cdot q + b \tag{1}$$

where a represents the slope of the cost curve and b represents the intercept. Depending on the case, we differentiate between the slope of the first stage a_1 and the second stage a_2. We assume that RE producers have zero marginal costs.

Each RE producer i allocates its production between the two stages. In the first stage, RE producers face production uncertainty, modeled as a normally distributed random variable:

$$Q_i \sim \mathcal{N}(\mu_{Q_i}, \sigma^2_{Q_i}), \tag{2}$$

where Q_i is the output of RE producer i, with an expected value μ_{Q_i} and standard deviation σ_{Q_i}. We abstract from withholding in the second market stage, that is, the total production must be sold after the second stage. The bid of RE producer i in the first stage is given by q_{i1} and the aggregate bid of all symmetric RE producers by $q_1 = \sum_i q_{i1}$.

The market clearing prices of both stages are derived from the intersection of the respective marginal cost curves and residual demand. In the first stage, conventional producers plan to produce $d - q_1$, and in the second stage adjust to meet the residual demand $d - Q$. We assume that the second-stage cost curve pivots around the clearing point of the first stage with slope a_2. The term $(a_1 - a_2) \cdot (d - q_{i1} - (N-1) \cdot q_{j1})$ in Equation 3b shifts the second-stage cost curve to the clearing point of the first stage.

The total profit of a RE producer i consists of revenues earned in the first and second stage. These are defined as follows:

$$\pi_{i1} = (a_1 \cdot (d - q_{i1} - (N-1) \cdot q_{j1}) + b) \cdot q_{i1}, \tag{3a}$$

$$\pi_{i2} = (a_2 \cdot (d - N \cdot Q_i) + b + (a_1 - a_2) \cdot (d - q_{i1} - (N-1) \cdot q_{j1})) \cdot (Q_i - q_{i1}), \tag{3b}$$

$$\pi_i = \pi_{i1} + \pi_{i2} \tag{3c}$$

with prices:

$$p_1(q_1) = a_1 \cdot (d - q_1) + b \tag{4a}$$

$$p_2(q_1) = a_2 \cdot (d - Q) + b + (a_1 - a_2) \cdot (d - q_1) \tag{4b}$$

RE producers bid a quantity in the first stage, which maximizes their utility U_i. In a risk-neutral setting the utility equals the total expected profits. Our central contribution is to extend this established framework by analyzing how risk-averse preferences affect bidding strategies. Risk-averse preferences of RE producers are modeled using a mean-variance utility function (cf. Markowitz 1991). In this setting, profit variance enters negatively in the utility function and is weighted with the degree of risk aversion λ.

$$U_i = \mathbb{E}[\pi_i] - \frac{\lambda}{2} \cdot \mathrm{Var}(\pi_i). \tag{5}$$

This approach is commonly used when assuming symmetric profit distributions. However, as q_{i1} enters quadratically into π_1 and π_2, the expected profit distribution is not necessarily symmetric. In classical portfolio theory, a standard metric for risk aversion with asymmetric profit distribution is conditional value at risk (CVaR), which takes tail risk into account (Rockafellar et al. 2000). However, we cannot solve the CVaR approach analytically, as the inverse cumulative density function of the profit is required. An approximation with the profit's skewness and kurtosis is also difficult to solve analytically, as terms above the fifth degree would result. Our numerical results show that the CVaR correlates strongly with variance. Therefore, we argue that using variance as a risk metric is a valid approximation to the CVaR approach (see Appendix A).

2.2. Model Specification

Our approach aims to investigate optimal bidding strategies of RE producers under risk aversion and imperfect competition. To extract the effects, we compare our results to optimal bids under risk-neutrality and vary the degree of competition between RE producers. In addition, we consider the effect of two other market conditions. One is the degree of flexibility of conventional producers to adjust their schedules on short notice. The other is the degree of homogeneity across RE producers. The two market conditions are specified below and Table 1 summarizes which assumptions are made in each case under investigation. A combination of the two market specifications is omitted due to limited additional effects[1].

Table 1: Overview of modeled cases

Assumption	**Case 1 (3.1)**	**Case 2 (3.2)**	**Case 3 (3.3)**
Conventional producer flexibility	Flexible ($a_1 = a_2$)	Inflexible ($a_2 > a_1$)	Flexible ($a_1 = a_2$)
Composition of RE producers	Homogeneous	Homogeneous	Heterogeneous

Conventional producer flexibility

In real-world electricity markets, the number of conventional power plants usually decreases as trading approaches delivery. Technical constraints on certain types of power plants prevent them from adjusting their production schedule on short notice. Another contributing factor is transaction costs. To account for the varying degree of participation in stage two, we define case 2 in which the slope of the second-stage cost curve exceeds that of the first-stage cost curve, i.e. $a_2 > a_1$. This setup enables us to investigate how the lack of flexibility in the second stage impacts the bidding behavior of RE producers under both risk neutrality and risk aversion.

[1]For further explanation see Section 4.

Composition of RE producers

In our basic model setup we assume equally large RE producers (case 1 and case 2). We relax this simplification by splitting the total amount of renewable electricity Q into two ownership categories (case 3). We interpret one part of Q as being owned by oligopolistic RE producers, who are able to exert market power. The number of oligopolistic RE producers is M. The quantity of renewable electricity from all oligopolistic producers is Q_M, and the quantity of an individual oligopolistic producer is Q_k. The remainder of renewable electricity is assumed to be owned by RE producers of atomistic size and thus represents a competitive fringe, unable to exert market power. We define this quantity as Q_F. The parameter s defines the share that splits Q into a quantity under oligopolistic and fringe producers:

$$Q_M = s \cdot Q \tag{6a}$$

$$Q_F = (1 - s) \cdot Q \tag{6b}$$

By assuming that a share of total renewable electricity bids the expected production μ_Q, we mimic a real-world setting in the German spot market. In the German market, a significant share of renewable electricity is marketed by transmission system operators (TSOs). The renewable energy regulation (§2 EEV) requires TSOs to offer the expected forecasted renewable electricity in the day-ahead market, so that deviations in quantities to the intraday market are minimized (Federal Ministry of Justice, Germany 2021). In our stylized analytical model, we seek to investigate the implication of a significant share of renewable electricity marketed with the expected value in the first market stage. Given this specification, Equation (7) defines the profit function of an oligopolistic RE producer k.

$$\begin{aligned}\pi_k = \; & [a_1 \cdot (d - q_{k1} - (M{-}1) \cdot q_{l1} - (1 - s) \cdot \mu_Q) + b] \cdot q_{k1} \\ & + \; [a_2 \cdot (d - Q) + b \\ & + (a_1 - a_2) \cdot (d - q_{k1} - (M{-}1) \cdot q_{l1} - (1 - s) \cdot \mu_Q)] \cdot (Q_k - q_{k1})\end{aligned} \tag{7}$$

An analysis of the market concentration for the direct marketing of solar PV and wind capacities in Germany indicates the potential to exert market power. The top three wind marketers held

26% of the total installed wind capacity in 2024, while the top ten wind marketers held 63%. The market concentration for solar PV is significantly lower with 15% marketed by the top three, and 25% marketed by the top ten solar PV marketers, respectively (Energie & Management 2025).

2.3. Numerical Assumptions

To visualize subsequent results, we feed our analytical model with numerical assumptions on each parameter. We choose a set of assumptions that reflects a common condition in many markets with moderate expected renewable output relative to demand.

Table 2: Numerical assumptions of parameters

Parameter	a_1	b	μ_Q	σ_Q	d
Value	0.4	20	40	6	100

Beyond techno-economic parameters, we assume a degree of risk aversion among RE producers which we derive using the certainty-equivalent-method. This method defines a guaranteed profit π_{gi}, an RE producer i would be indifferent between accepting or rejecting compared to an uncertain profit π_i.

$$\pi_{gi} = E[\pi_i] - \frac{1}{2} \cdot \lambda \cdot \sigma_{\pi_i}^2 \tag{8}$$

To calculate a degree of risk aversion, we assume that an RE producer is indifferent between a certain profit equal to the expected profit minus one standard deviation and the uncertain profit π_i ($\pi_{gi} = E[\pi_i] - \sigma_{\pi_i}$). The exact choice of the degree of risk aversion λ is secondary, as, in our analysis, it is mainly required for visualizing the results. Given the numerical assumptions outlined in Table 2 we can calculate the expected profit, standard deviation, and variance for a number of RE producers N. In a monopolistic market setting with $N = 1$, the degree of risk aversion amounts to $\lambda_1 = 0.011$. The number of RE producers influences the distribution of expected profits, as market power, and the degree of withholding vary. For $N = 64$, using the same rationale, the degree of risk aversion is $\lambda_{64} = 0.0091$ (see Appendix B). Thus, we choose $\lambda = 0.01$ as a reasonable estimate for the degree of risk aversion.

3. Results

This section presents the model results of the three cases defined in subsection 2.2. Crucially, for all cases, we establish the risk-neutral solutions ($\lambda = 0$) by replicating the established literature as a baseline, and then compare these to our main results under risk aversion ($\lambda > 0$). We begin with the first case analyzing homogeneous risk-averse RE producers facing equal cost curves of conventional producers in the two market stages. We then introduce different slopes of the conventional cost curves in the first and second stage to study the effects of inflexibility as delivery approaches. In a third step, we add RE producer heterogeneity by distinguishing between oligopolistic and fringe RE producers. For all three model setups we calculate the optimal bidding strategy for RE producers and resulting market prices. Finally, we evaluate the implications of bidding strategies in terms of consumer and producer surplus as well as welfare.

3.1. Case 1: Risk-averse renewable oligopoly - flexible conventional production and homogeneous composition of RE producers

In the first model specification, we assume identical cost functions of conventional producers in the two market stages ($a_1 = a_2 = a$) and homogeneous composition of RE producers. Proposition 1 shows the optimal bidding strategy for an RE producer in the first stage.

Proposition 1. *Under above assumptions, the profit-maximizing quantity for a risk-averse renewable oligopolist in the first stage is* q^*_{i1}.

$$q^*_{i1} = \frac{\mu_Q N + \lambda[\sigma^2_Q(2\mu_Q a - ad - b)]}{N\left(N + \lambda\sigma^2_Q a + 1\right)} \tag{9}$$

Proof. The profit function of RE producer i is described in Eq. (3). Given $a_1 = a_2$, we can simplify the profit function for RE producer i to:

$$\pi_i = \ [a \cdot (d - q_{i1} - (N-1) \cdot q_{j1}) + b] \cdot q_{i1} + \ [a \cdot (d - N \cdot Q_i) + b] \cdot (Q_i - q_{i1}) \tag{10}$$

The profit maximizing quantity results from the derivative of the utility function (Eq. (5)) with respect to q_{i1}:

$$\frac{dU_i}{dq_{i1}} = \frac{d\mathbb{E}(\pi_i)}{dq_{i1}} - \frac{\lambda}{2}\frac{d\mathrm{Var}(\pi_i)}{dq_{i1}} \tag{11}$$

with

$$\frac{d\mathbb{E}(\pi_i)}{dq_{i1}} = a \cdot (N\mu_{Q_i} - 2q_{i1} - (N-1)q_{j1}) \tag{12}$$

and

$$\frac{d\text{Var}(\pi_i)}{dq_{i1}} = 2N\sigma_{Q_i}^2 a\left(-2\mu_{Q_i}Na + Naq_{i1} + ad + b\right) \tag{13}$$

Setting the derivative of U_i to zero and solving for q_{i1}^*results in the profit maximizing first-stage bid of RE producer i:

$$q_{i1}^* = \frac{2\mu_{Q_i}N^2\sigma_{Q_i}^2 a\lambda + \mu_{Q_i}N - N\sigma_{Q_i}^2 ad\lambda - N\sigma_{Q_i}^2 b\lambda - (N-1)q_{j1}}{N^2\sigma_{Q_i}^2 a\lambda + 2}. \tag{14}$$

Applying the symmetry assumption ($q_{i1} = q_{j1}$, $\mu_Q = \mu_{Qi} * N$, and $\sigma_Q = \sigma_{Qi} * N$), we obtain Eq. (9):

$$q_{i1}^* = \frac{\mu_Q N + \lambda[\sigma_Q^2(2\mu_Q a - ad - b)]}{N\left(N + \lambda\sigma_Q^2 a + 1\right)}$$

Since $\lambda > 0$ and $a > 0$, the second derivative of U_i is negative (Eq. (15)).

$$\frac{d^2U_i}{dq_{i1}^2} = -2a - \frac{\lambda}{2}2N^2a^2\sigma_{Q_i}^2 \tag{15}$$

Therefore, q_i^* is the profit-maximizing quantity. ■

For the aggregated first-stage bid of all RE producers, q_1^*, the term N in the denominator of Eq. (9) cancels out. In the case of perfect competition ($N \to \infty$), it can be shown that $N \cdot q_{i1}^*$ converges to the expected value μ_Q (Eq. (16)). This implies that risk aversion has no effect on bidding behavior under perfect competition.

$$\lim_{N\to\infty} N \cdot q_{i1}^* = \lim_{N\to\infty} \frac{\mu_Q N^2}{N^2} = \mu_Q \tag{16}$$

Corollary 1. *Under risk aversion and flexible conventional production ($a_1 = a_2 = a$), the first-stage equilibrium price p_1^* is given by $p_1^* = a\left(d - \frac{\mu_Q N + \lambda\sigma_Q^2(2\mu_Q a - ad - b)}{N + \lambda\sigma_Q^2 a + 1}\right) + b$. The expected forward premium FP, defined as $\mathbb{E}[p_1^* - p_2(Q)]$, is positive and increases in the degree of risk aversion λ if $d > \mu_Q \frac{N+2}{N+1} - \frac{b}{a}$. Since p_1^* is linearly related to q_1^* and the second-stage price is independent of q_1^*, we can conclude that q_1^* decreases in the degree of risk aversion if $d > \mu_Q \frac{N+2}{N+1} - \frac{b}{a}$.*

Proof. By plugging in the optimal first-stage quantity of Eq. (9) into the Eq. (4a), we obtain the first-stage equilibrium price. The substraction of the expected second-stage price from the first-stage equilibrium price results in the expected forward premium (Eq. (17)).

$$
\begin{aligned}
FP &= p_1^* - \mathbb{E}[p_2] \\
&= a\left[d - \frac{\mu_Q N + \lambda\sigma_Q^2\,(2\mu_Q a - ad - b)}{N + \lambda\sigma_Q^2 a + 1}\right] + b - \mathbb{E}\left[a(d - Q) + b\right] \\
&= a\left[\mu_Q - \frac{\mu_Q N + \lambda\sigma_Q^2(2\mu_Q a - ad - b)}{N + \lambda\sigma_Q^2 a + 1}\right]
\end{aligned} \tag{17}
$$

To receive the impact of risk aversion on the forward premium, we take the derivative of the forward premium FP, with respect to λ:

$$
\begin{aligned}
\frac{\partial FP}{\partial \lambda} &= -a \cdot \frac{d}{d\lambda}\left(\frac{\mu_Q N + \lambda\sigma_Q^2(2\mu_Q a - ad - b)}{N + \lambda\sigma_Q^2 a + 1}\right) \\
&= -a \cdot \frac{\sigma_Q^2\left[(2\mu_Q a - ad - b)(N + \lambda\sigma_Q^2 a + 1) - a\mu_Q N - a\lambda\sigma_Q^2(2\mu_Q a - ad - b)\right]}{(N + \lambda\sigma_Q^2 a + 1)^2} \\
&= -a \cdot \frac{\sigma_Q^2\left[(2\mu_Q a - ad - b)N + (2\mu_Q a - ad - b) - a\mu_Q N\right]}{(N + \lambda\sigma_Q^2 a + 1)^2}
\end{aligned} \tag{18}
$$

The denominator is positive. The forward premium rises with the degree of risk aversion if:

$$
\frac{\partial FP}{\partial \lambda} > 0 \iff -a \cdot \sigma_Q^2\left[(2\mu_Q a - ad - b)(N + 1) - a\mu_Q N\right] > 0 \tag{19}
$$

Together with $a > 0$ and $\sigma_Q^2 > 0$:

$$
(2\mu_Q a - ad - b)(N + 1) - a\mu_Q N < 0 \tag{20}
$$

Reformulate:

$$
(2\mu_Q a - ad - b)(N + 1) < a\mu_Q N \tag{21a}
$$

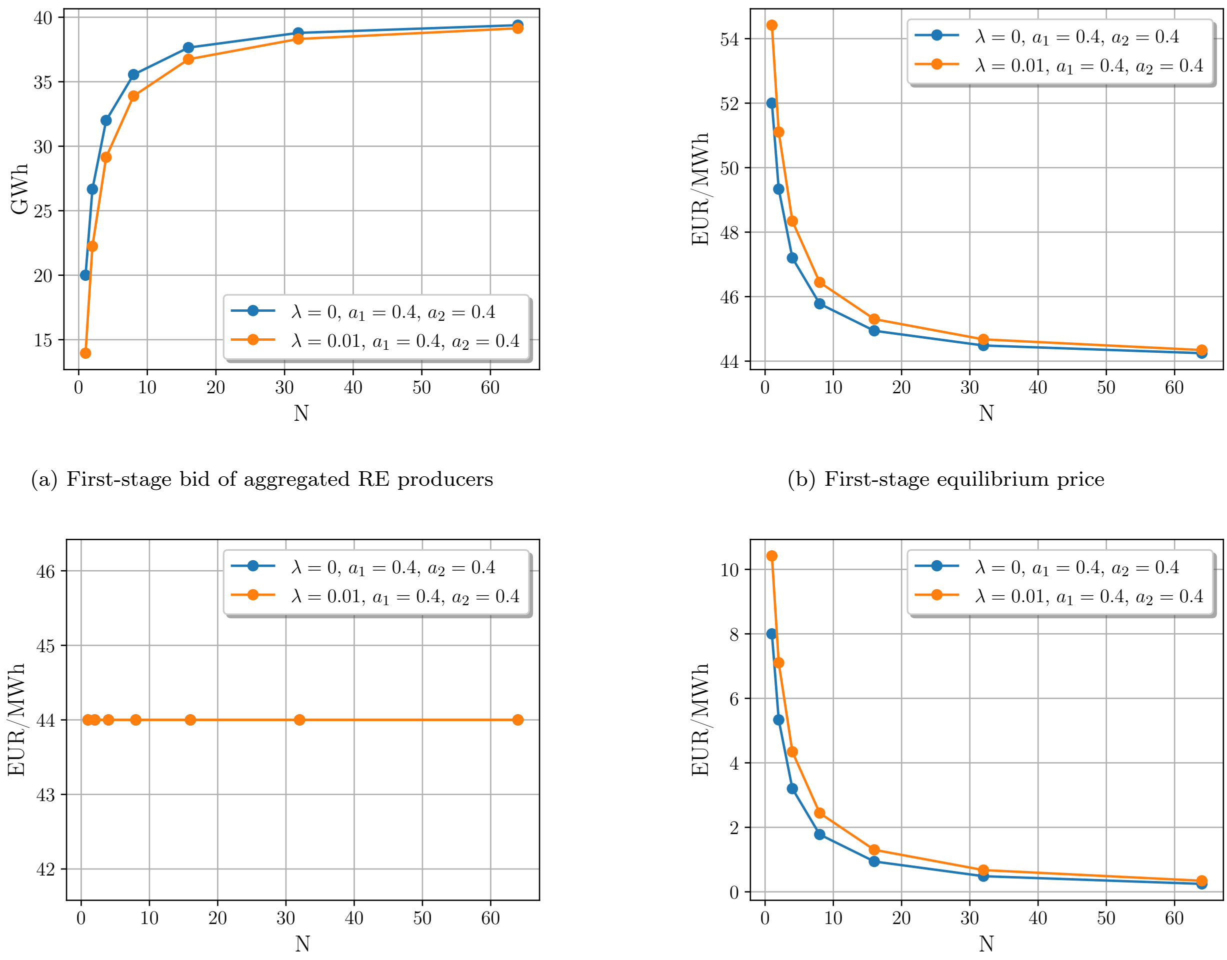
$$
2\mu_Q a(N + 1) - ad(N + 1) - b(N + 1) < a\mu_Q N \tag{21b}
$$

$$
-ad(N + 1) < a\mu_Q N - 2\mu_Q a(N + 1) + b(N + 1) \tag{21c}
$$

$$
d > \mu_Q \frac{N + 2}{N + 1} - \frac{b}{a} \tag{21d}
$$

■

If the demand d is sufficiently large compared to expected renewable output μ_Q, the forward premium rises with the degree of risk aversion. The rationale is that risk-averse producers withhold even more in the first stage to reduce profit variance. This leads to an increase in p_1^*, while the expected second-stage price remains independent of the first-stage bid.



(a) First-stage bid of aggregated RE producers

(b) First-stage equilibrium price

(c) Expected second-stage price

(d) Expected forward premium

Figure 1: Results under identical supply curve slopes in stage one and two for risk-averse and risk-neutral producers: bids, prices, and forward premium

Note: N is the number of symmetric RE producers. λ is the coefficient of risk aversion. Results are based on a numerical example with the following parameter values: $a_1 = a_2 = a = 0.4$, $b = 20$, $d = 100$, $\mu_Q = 40$ and $\sigma_Q = 6$. The blue line represents the risk-neutral case, whereas the orange line corresponds to risk-averse RE producers.

Figure 1 illustrates the effects of risk aversion ($\lambda > 0$) in comparison to risk-neutrality ($\lambda = 0$) in a setting with N symmetric RE producers and identical cost curves in both market stages ($a_1 = a_2 = a$). Figure 1 (a) shows that risk-averse producers (orange line) withhold more quantity in the first stage compared to the risk-neutral case (blue line). This behavior arises because withholding reduces the variance of profits, which risk-averse producers seek to avoid. As a result, the aggregate forward supply decreases. This extends earlier findings from the literature (Knaut and Obermüller 2016;

Ito and Reguant 2016). As the number of RE producers N increases and competition intensifies, the effect diminishes. Figure 1 (b) demonstrates the effect of the bidding behavior on prices: The reduced first-stage bid leads to higher first-stage market-clearing prices, ceteris paribus. As risk-averse producers bid lower quantities to limit profit variability, aggregate supply decreases, pushing first-stage prices upward. Thus, risk aversion systematically raises first-stage prices in the presence of market power. In contrast, Figure 1 (c) shows that the expected second-stage price remains unchanged under risk aversion (the blue and orange lines overlap). This holds under two conditions: the second-stage cost curve is identical to the first-stage cost curve, and RE producers must sell their entire generation in the second-stage market. Figure 1 (d) displays the expected forward premium. The premium increases with the degree of risk aversion, as strategic withholding in the first stage shifts first-stage prices upward. In this sense, risk-averse behavior by symmetric RES producers in an oligopoly induces a higher premium than under risk neutrality.[2] However, similar to the case assuming risk-neutral RE producers, the premium converges to zero under perfect competition.

3.2. Case 2: Risk-averse renewable oligopoly - inflexible conventional production and homogeneous composition of RE producers

In this case, we introduce a decrease in flexibility of the conventional production in the second stage. We model this by increasing the slope of the second-stage cost curve relative to that of the first-stage cost curve ($a_2 > a_1$). This reflects more realistic market conditions, where second-stage participation is often limited. The following proposition characterizes the optimal first-stage bid under risk aversion for a single RE producer i:

Proposition 2. *The profit-maximizing quantity for a risk-averse RE oligopolist in the first stage is q^*_{i1}, as shown in Eq. (C.7):*

$$q^*_{i1} = \frac{A + \lambda B}{C + \lambda D} \tag{22}$$

[2] As already shown this result holds if the demand is sufficiently large compared to expected renewable output (see Corollary 1).

where the components are defined as follows:

$$
\begin{aligned}
A &= \mu_Q N(Na_2 + a_2 - a_1)\\
B &= \sigma_Q^2\Big(2\mu_Q N a_2^2 - 2\mu_Q a_1 a_2 + 2\mu_Q a_2^2 - N a_1 d a_2 - N b a_2 + a_1^2 d + a_1 b - a_1 d a_2 - b a_2\Big)\\
C &= N(N^2 a_2 + N a_2)\\
D &= N\Big(\sigma_Q^2\Big(-N a_1 a_2 + 2N a_2^2 + a_1^2 - 3a_1 a_2 + 2a_2^2\Big)\Big)
\end{aligned}
$$

Proof. See Appendix C. ∎

In the limit of perfect competition ($N \to \infty$), $N \cdot q_{i1}^*$ converges to the expected value μ_Q, similar to (16). Hence, even in the presence of inflexible conventional producers, risk aversion has no effect on bidding behavior under perfect competition.

Corollary 2. *Under above assumptions, the optimal first-stage bid of a monopolist decreases in the degree of risk aversion if* $\mu_Q < \frac{2a_2(a_1 d + b)}{a_1(4a_2 - a_1)}$. *The expected forward premium increases with the degree of risk aversion, if the condition holds.*[3]

Proof. From Eq. 21, we learn that the condition under which risk aversion lowers the first-stage bid relaxes with higher N. The same holds for the following proof. To simplify the calculation, we look at the most conservative condition assuming $N = 1$.

$$\frac{dq_{i1}^*}{d\lambda} = \frac{BC - AD}{(2a_2 + \lambda D)^2} \tag{23}$$

With (assuming N=1):

$$
\begin{aligned}
B &= \sigma_Q^2\left[\mu_Q(4a_2^2 - 2a_1 a_2) + (-2a_1 d a_2 - 2b a_2 + a_1^2 d + a_1 b)\right] && \text{(24a)}\\
C &= 2a_2 && \text{(24b)}\\
A &= \mu_Q(2a_2 - a_1) && \text{(24c)}\\
D &= \sigma_Q^2(2a_2 - a_1)^2 && \text{(24d)}
\end{aligned}
$$

See Appendix D for reformulation of $\frac{dq_{i1}^*}{d\lambda}$.
$\frac{dq_{i1}^*}{d\lambda} < 0$ if:

$$\mu_Q < \frac{2a_2(a_1 d + b)}{a_1(4a_2 - a_1)}, \tag{25}$$

The condition in Eq. 25 holds under common market conditions. We further test two edge cases i) $a_2 = a_1$ and ii) $a_2 >> a_1$:
For i) the expression becomes the same as in Eq. 21:

$$\mu_Q < \frac{2(a_1 d + b)}{3a_1} \tag{26}$$

[3] It can be shown that this condition becomes weaker for higher N.

For ii) the expression becomes:

$$\mu_Q < \frac{da_1 + b}{2a_1} \tag{27}$$

Given that q_1 decreases in λ, prices and the expected forward premium become:

$$p_1(q_1^*) = a_1(d - q_1^*) + b \tag{28a}$$
$$\mathbb{E}(p_2(q_1^*, q_2)) = a_2(d - \mu_Q) + b + (d - q_1^*)(a_1 - a_2) \tag{28b}$$
$$\mathbb{E}(FP) = a_2(\mu_Q - q_1^*) \tag{28c}$$

Since the expected forward premium is a linear function of q_1^*, and $a_2 > 0$, the expected forward premium increases in the degree of risk aversion, if the condition in Eq. 25 holds.

■

Similar to subsection 3.1, risk aversion reduces the first-stage bid if demand is sufficiently large compared to expected renewable output.

Corollary 3. *Under risk aversion and imperfect competition, the optimal first-stage bid increases with lower flexibility of conventional production in the second stage, represented by an increase in a_2, if the condition in Equation (31) holds. A higher first-stage bid decreases the first-stage price. However, the second-stage price decreases more than the first-stage price, since $a_2 > a_1$. Thus, we can conclude that the expected forward premium increases with reduced flexibility under the aforementioned condition.*

Proof.

$$q_{i1}^* = \frac{\mu_Q(2a_2 - a_1) + \lambda\Big[\sigma_Q^2(4\mu_Q a_2^2 - 2\mu_Q a_1 a_2 - a_1 d a_2 - b a_2 + a_1^2 d + a_1 b)\Big]}{2a_2 + \lambda\Big[\sigma_Q^2(-a_1 a_2 + 2a_2^2 + a_1^2 - 3a_1 a_2 + 2a_2^2)\Big]} \tag{29}$$

From following definitions:

$$A = \mu_Q(2a_2 - a_1) + \lambda\sigma_Q^2(4\mu_Q a_2^2 - 2\mu_Q a_1 a_2 - a_1 d a_2 - b a_2 + a_1^2 d + a_1 b) \tag{30a}$$
$$B = 2a_2 + \lambda\sigma_Q^2(4a_2^2 - 4a_1 a_2 + a_1^2) \tag{30b}$$
$$A' = 2\mu_Q + \lambda\sigma_Q^2(8\mu_Q a_2 - 2\mu_Q a_1 - a_1 d - b) \tag{30c}$$
$$B' = 2 + \lambda\sigma_Q^2(8a_2 - 4a_1) \tag{30d}$$

follows:

$$\frac{dq_{i1}^*}{da_2} > 0 \iff \frac{A'B - AB'}{B^2} > 0 \iff A'B - AB' > 0. \tag{31}$$

The condition at which the corollary holds is highly complex. However, we show numerically that it holds even under extreme parameterization in the degree of risk aversion and for various levels of expected RE production (s. Figure 2).

■

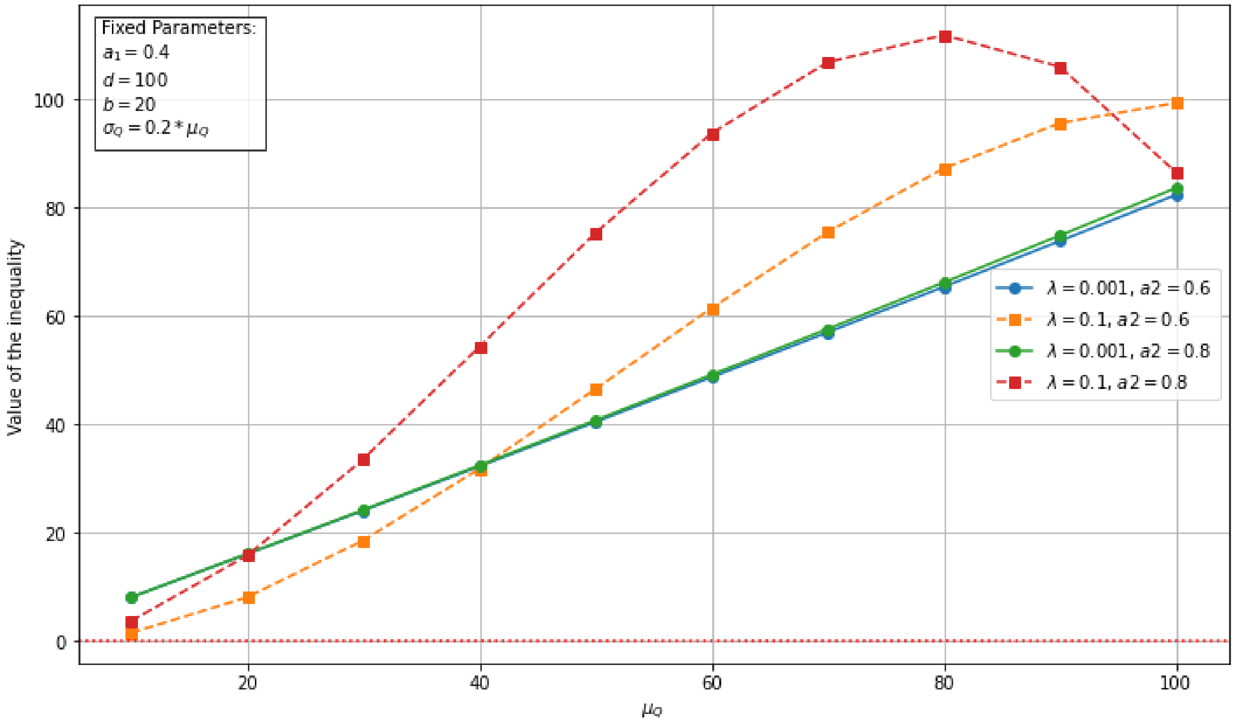
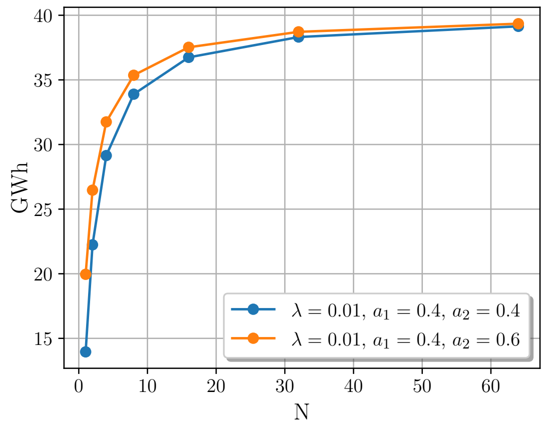
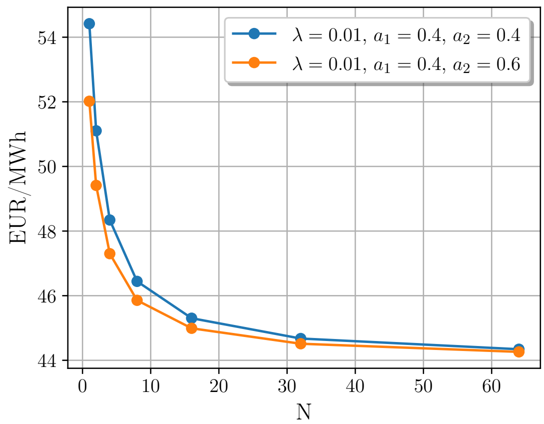


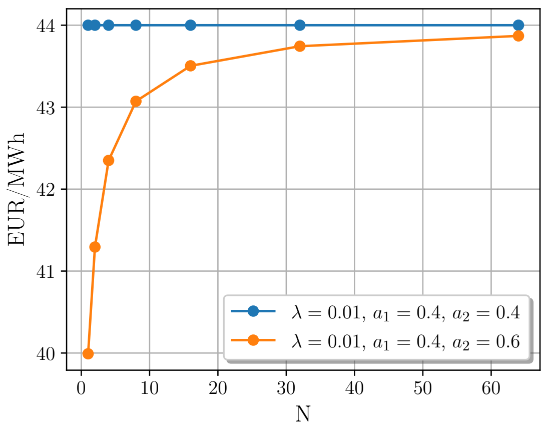
Figure 2: Numerical assessment of inequality 31



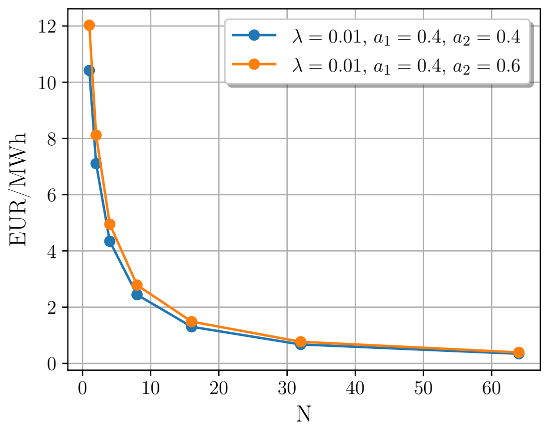
(a) First-stage bid of aggregated RE producers



(b) First-stage equilibrium price



(c) Expected second-stage price



(d) Expected forward premium

Figure 3: Results under risk aversion and inflexible supply curve: bids, prices, and forward premium

Note: N is the number of symmetric RE producers. λ is the coefficient of risk aversion. Results are based on a numerical example with the following parameter values: $a_1 = 0.4$, $a_2 = [0.4; 0.6]$, $b = 20$, $d = 100$, $\mu_Q = 40$ and $\sigma_Q = 6$.

Figure 3 illustrates the effects of risk aversion ($\lambda > 0$), where the second-stage supply curve is steeper than the first-stage supply curve ($a_2 > a_1$). This setting reflects limited flexibility in the second-stage market, i.e. the intraday market. Figure 3 (a) shows that when the second-stage supply is less flexible than the first-stage supply ($a_2 > a_1$), producers anticipate higher repurchase costs and withhold less in the forward market compared to the case of flexible conventional producers. Thus the first-stage bids of aggregated RE producers are higher with inflexible conventional producers (orange line above the blue line). Figure 3 (b) demonstrates that the reduced withholding under asymmetric slopes dampens first-stage prices compared to the case of flexible conventional producers. Figure 3 (c) highlights the price effect in the second stage. When supply slopes differ, the first-stage price influences the intercept of the second-stage supply curve. Withheld quantities are fully sold in the less flexible second stage, where they face a steeper slope, resulting in lower second-stage prices. Under perfect competition ($N \to \infty$), differing slopes have no effect, and prices converge to the competitive outcome. Figure 3 (d) shows that under risk aversion a higher (a_2/a_1) ratio leads to stronger price effects and thus larger premia (orange line above blue line).[4] Again, these premia converge to zero under perfect competition.

3.3. Case 3: Risk-averse renewable oligopoly - flexible conventional production and heterogeneous composition of RE producers

In cases 1 and 2 we treat all RE producers as symmetric. To approximate real-world German spot-market practice, where TSOs are required to offer the expected output of RE in the day-ahead market, we now assume that a certain share of the total RE generation is marketed based on its expected value. Fringe producers (or TSOs acting on their behalf) bid their expected generation in the first stage. The remaining share is supplied by a group of symmetric, oligopolistic RE producers. This hybrid setup better reflects actual market conditions, with M denoting the number of oligopolistic RE producers. The parameter s defines the share of total RE output subject to strategic behavior. As in our first case, we assume flexible conventional producers, which implies $a_1 = a_2 = a$.

As the fringe bid is fixed to the expected value $(1 - s) \cdot \mu_Q$, the first-stage price is determined as:

$$p_1 = a_1 \cdot (d - q_{k1} - (M - 1) \cdot q_{l1} - (1 - s) \cdot \mu_Q) + b \tag{32}$$

which is structurally equivalent to the price under symmetric-oligopoly from case 1, after (i) shifting the effective demand intercept by $d \mapsto d - (1 - s) \cdot \mu_Q$ and (ii) replacing the number of strategic firms N with M.

[4] This result holds under Eq. (31) (see Corollary 3).

Since the fringe bid only shifts the intercept of residual demand, all first-order conditions, and thus all comparative-static results on risk aversion, flexibility, prices, and forward premia, carry over directly from case 1 under the substitutions $d \mapsto d - (1-s) \cdot \mu_Q$ and $N \mapsto M$. Accordingly, in this hybrid setting with a competitive fringe bidding the expected value, $(1-s) \cdot \mu_Q$, in the first stage, the profit-maximizing bid of each oligopolistic RE producer is given by Proposition 1 after the substitutions $d \mapsto d-(1-s) \cdot \mu_Q$ and $N \mapsto M$. Thus, the analytical results from the symmetric case remain applicable, providing a consistent foundation for interpretation.

As in case 1, we derive numerical results for this setting. The qualitative patterns remain unchanged: risk-averse RE producers reduce their first-stage bids, raising first-stage prices and leading to a positive forward premium. This premium decreases with increasing competition and vanishes in the limit of perfect competition. However, a significant distributional effect arises in this framework with respect to the rents of RE producers, discussed in detail in subsection 3.5.

3.4. Rents and welfare implications of Case 1 and 2

So far, we have examined how risk aversion and market structure shape the bidding behavior of RE producers, market prices in the first and second stage, and the resulting forward premium. We now turn to the implications of these findings for welfare outcomes and the distribution of rents among market participants, specifically conventional producers, RE producers, and consumers.

Figure 4 provides a comprehensive overview of the results. It displays producer surplus (separately for RE and conventional producers), consumer surplus, and total welfare across four scenarios: risk neutrality vs. risk aversion, each under flexible and inflexible conventional producers. At this stage, we focus on the case of symmetric RE producers.

Producer surupls

The total producer surplus consists of the surplus earned by RE producers as well as conventional producers. RE producers sell part of their uncertain output Q in the first stage and the remainder in the second stage. They face no marginal costs and operate under uncertainty. Their expected producer surplus is given by:

$$\mathbb{E}[\Pi_R(q_1)] = p_1 q_1 + \mathbb{E}[p_2(Q - q_1)] \tag{33}$$

The expected conventional producer surplus is given by:

$$\mathbb{E}[\Pi_C(q_1)] = p_1(d - q_1) - C_1(q_1) + \mathbb{E}[p_2(q_1 - Q)] - \mathbb{E}[C_2(q_1)] \tag{34}$$

Eq. (34) defines the expected conventional producer surplus, accounting for both market stages. We obtain the costs in the first stage by integrating over the marginal cost function:

$$C_1(q_1) = \frac{1}{2}a_1(d - q_1)^2 + b_1(d - q_1) \tag{35}$$

The expected cost function for the second stage is:

$$\begin{aligned}\mathbb{E}[C_2(q_1)] = \mathbb{E}\Bigg[&\frac{1}{2}a_2\left(d^2 - 2d\mu + \mu^2 + \sigma^2 - (d - q_1)^2\right) \\ &+ (a_1 - a_2)(d - q_1)(q_1 - Q) + b(q_1 - Q)\Bigg]\end{aligned} \tag{36}$$

By inserting Eqs. (36) and (35) in Eq. (34) we obtain the conventional producer surplus. By further plugging in the optimal quantity, we can quantify the producer surplus of RE and conventional producers.

Figure 4 (a) illustrates the effects of risk aversion and flexibility of the supply curve on the surplus of RE producers. For small values of N, risk aversion leads to lower rents. In our parameterization, the first-stage bid of a risk-averse monopolist is significantly lower than that of a risk-neutral monopolist. This behaviour reduces profit variance, but also significantly reduces first-stage revenues. However, as N increases, first-stage bids of RE producers under risk aversion also increase, and their surplus increases to the point at which they cumulatively bid the optimal quantity under a risk-neutral monopoly. From this point onward, the surplus of risk-averse oligopolists is higher than the surplus of risk-neutral ones, as the need to reduce profit variance through lower first-stage bids generates higher overall revenues. Inflexible conventional producers (i.e., $a_2 > a_1$) consistently reduce RE producer surplus, regardless of the degree of risk aversion, as the inflexibility increases first-stage bids.

Figure 4 (b) shows that the surplus of conventional producers increases under risk aversion. This is due to higher first-stage prices caused by RE producers' strategic withholding. As with RE producers, conventional producer surplus declines when supply curves are steeper in the second stage, reflecting higher adjustment costs and reduced flexibility. However, as the number of producers increases, the surplus converges across all cases, indicating that market power diminishes and price effects become negligible in the limit of perfect competition.

Consumer surplus

Following standard practice in electricity market modeling, we assume that consumer demand is inelastic. This implies that electricity is consumed in full up to a price threshold defined by the value of lost load (p^{VOLL}), which reflects the maximum willingness to pay for uninterrupted supply. Under this assumption, consumer surplus in the first stage is given by the product of the difference between the value of lost load and the market-clearing price, and the total demand level ($(p^{VOLL} - p_1) \cdot d$) (Knaut and Obermüller 2016). By substituting the equilibrium first-stage price $p_1(q_{i1}^*) = a_1 \cdot (d - q_1^*) + b$, consumer surplus can be expressed as:

$$CS = (p^{VOLL} - a_1 \cdot d - b + a_1 \cdot q_1^*) \cdot d \tag{37}$$

By further plugging in the optimal quantity q_1^*, we can quantify the consumer surplus. As earlier results have shown, the optimal quantity q_1^*, and hence the resulting consumer surplus, depends on the underlying market configuration, such as the degree of risk aversion or the slope asymmetry between the two market stages.

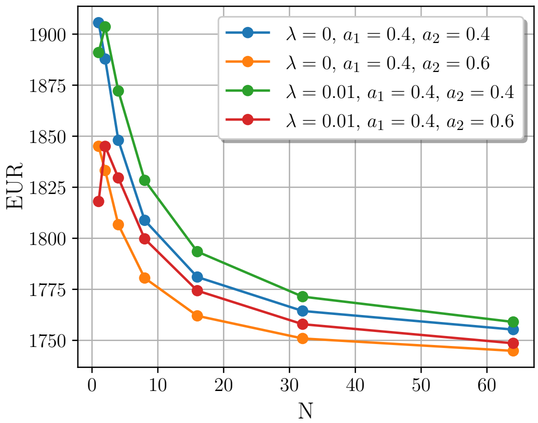
Figure 4 (c) illustrates the effects of risk aversion and market structure on consumer surplus. Risk-averse producers strategically withhold quantities in the first stage to hedge against uncertainty. Prices then increase, leading to a decline in consumer surplus compared to the risk-neutral benchmark. However, consumer surplus increases with a larger number of RE producers, as increased competition reduces market power and puts downward pressure on first-stage prices. This relationship is particularly pronounced under inflexible supply conditions, consistent with findings by Knaut and Obermüller (2016), and it remains robust even when producers are risk-averse. Nevertheless, overall consumer surplus tends to be lower under risk aversion due to reduced first-stage supply and higher first-stage prices.

Welfare

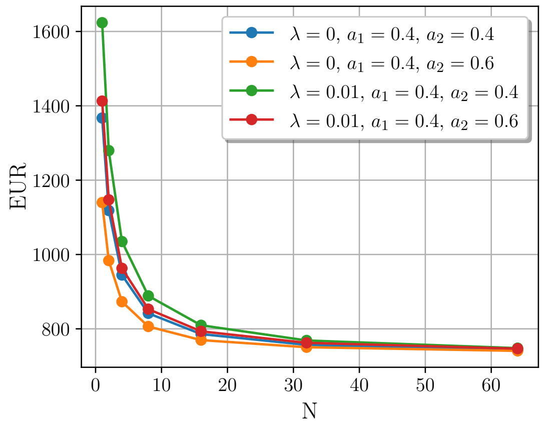
Combining the effects on producer and consumer surplus allows us to assess the implications for overall welfare. Changes in total welfare indicate efficiency losses or gains due to strategic behavior, risk aversion, or market structure. The overall expected welfare can be defined as:

$$\mathbb{E}[W(q_1)] = \mathbb{E}[\Pi_R(q_1)] + \mathbb{E}[\Pi_C(q_1)] + \mathbb{E}[CS(q_1)] \tag{38}$$

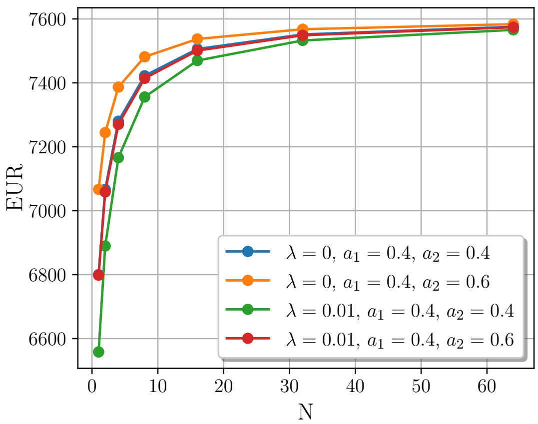
Corollary 4. *When supply slopes are identical ($a_1 = a_2$), risk aversion has no effect on overall welfare compared to the risk-neutral case. A steeper second-stage supply curve ($a_2 > a_1$) reduces welfare relative to the flexible benchmark due to higher adjustment costs. Under risk aversion, welfare declines further in oligopolistic settings, as producers withhold more and amplify inefficiencies.*



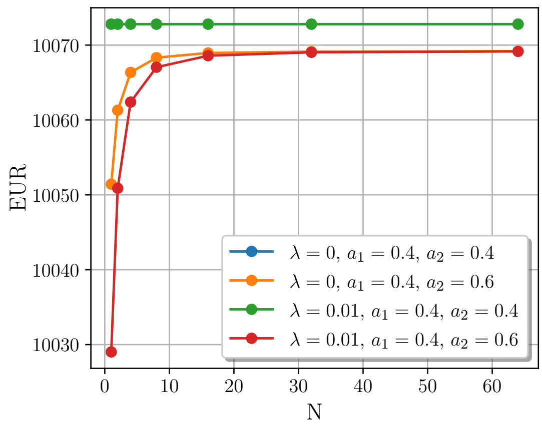
(a) RE producer surplus



(b) Conventional producer surplus



(c) Consumer surplus



(d) Welfare

Figure 4: Results under risk aversion and (in)fexible supply curve: producer surplus, consumer surplus, and welfare

Note: N is the number of symmetric RE producers. λ is the coefficient of risk aversion. Results for an example with $a_1 = 0.4$, $a_2 = [0.4; 0.6]$, $b = 20$, $d = 100$, $\mu_Q = 40$, $\sigma_Q = 6$ and $p^{VOLL} = 120$.

Figure 4 (d) summarizes the effects on total welfare. In line with Knaut and Obermüller (2016), we find that when the supply slopes in both market stages are identical ($a_1 = a_2$), market power alone does not reduce welfare under risk neutrality. We extend this result by showing that this welfare invariance also holds under risk aversion: the blue (risk-neutral) and green (risk-averse) lines in the figure coincide, indicating that strategic withholding does not influence welfare as long as the conventional producers are fully flexible.

However, when conventional producers are inflexible ($a_2 > a_1$), total welfare declines. Since RE producers bid more in the first stage, prices overall decrease, increasing consumer surplus. RE and conventional producers' surplus decreases by a larger amount, decreasing overall welfare. Risk-averse behavior reinforces this effect by inducing greater quantity withholding in the first stage. As the number of producers decreases, these distortions intensify due to greater market power. Thus, our results highlight that the interaction of risk aversion and supply-side inflexibility leads to welfare losses (red line) beyond those attributable to market power alone.

3.5. Rents and welfare implications of Case 3

This section explores the welfare and rent distribution through a heterogeneous market structure in the presence of risk aversion (case 3). In particular, we analyze how strategic withholding by risk-averse and oligopolistic RE producers affects their surplus, the surplus of competitive fringe producers, conventional producers, and consumers. Figure 5 illustrates the distributional effects of risk aversion and flexible conventional producers in a setting with both oligopolistic and competitive RE producers.

The total producer surplus in this setup consists of the surpluses of oligopolistic RE producers, fringe RE producers, and conventional producers.

The surplus of oligopolistic RE producers is given by the following Eq.:

$$\mathbb{E}[\Pi_{\mathrm{R,olig}}(q_1)] = p_1 \cdot M \cdot q_{i1} + \mathbb{E}\left[p_2 \cdot (Q - M \cdot q_{i1})\right] \tag{39}$$

with:

$$p_1 = a_1 \cdot (d - \mu_Q - M \cdot q_{i1}) + b, \tag{40a}$$

$$p_2 = a_2 \cdot (d - 2 \cdot Q) + b \tag{40b}$$

As in case 1 and 2 they face no marginal costs and operate under uncertainty. By plugging in the optimal bid quantity, we can quantify the producer surplus of oligopolistic RE producers.

The expected producer surplus of fringe RE producer is given by:

$$\mathbb{E}[\Pi_{\mathrm{R,fringe}}(q_1)] = p_1 \cdot \mu_Q + \mathbb{E}[p_2(Q - \mu_Q)] \tag{41}$$

where p_1 and p_2 are analoug to Eqs. 40. Fringe producers behave competitively and bid their expected output μ_Q in the first stage. Since they cannot influence the price strategically, their surplus depends entirely on price levels influenced strategically by the oligopolists. As risk aversion leads to more withholding by strategic producers, fringe producers indirectly benefit from the resulting price increase.

The expected conventional producer surplus is given by:

$$\mathbb{E}[\Pi_C(q_1)] = p_1 \cdot (d - M \cdot q_{i1} - \mu_Q) - C_1(q_1) + \mathbb{E}[p_2(M \cdot q_{i1} + \mu_Q - 2Q)] - \mathbb{E}[C_2(q_1)] \tag{42}$$

The cost function in the first stage and the expected cost function for the second stage are analogous to (35) and (36), respectively, with the substitution of $q_1 \mapsto m \cdot q_1 - \mu_Q$.

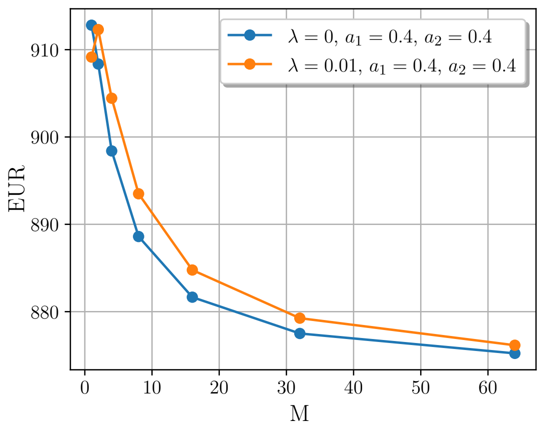
In the first stage, conventional producers supply the residual demand not covered by RE producers. In the second stage, they adjust output in response to deviations in renewable production.

Corollary 5. *Fringe RE producers benefit from the market power exerted by oligopolistic RE producers, as higher first-stage prices increase their revenues. This effect is amplified when oligopolistic producers are risk averse and strategically reduce their forward commitments.*

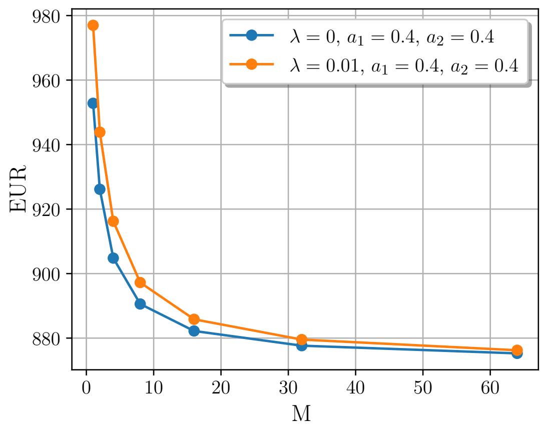
As in the previous results, a smaller number of strategic producers implies greater market power and more pronounced withholding in the first stage. This results in higher first-stage prices and larger expected forward premia. Consequently, fringe producers benefit from concentrated market structures: they bid their expected output without strategically influencing the price, yet receive higher prices due to the actions of the oligopolists. This relationship is reflected in Figure 5 (b), where fewer oligopolistic producers lead to a higher surplus for fringe suppliers. A similar pattern emerges for conventional producers in Figure 5 (c): lower competition among renewables leads to a higher first-stage price and a higher surplus. Thus, both fringe and conventional producers benefit from the exercise of market power by a few strategic RE producers. Comparing the risk-neutral and risk-averse cases reveals that the surplus of competitive RE producers is higher when the oligopolists are risk-averse (the orange line lies above the blue one). Again, more aggressive withholding of risk-averse RE producers raises first-stage prices and thereby increases the rents of price-taking producers.

Consumer surplus and total welfare are computed analogously to the previous cases. Specifically, the structure of the equations remains unchanged, only the relevant prices and quantities reflecting the heterogeneous market setup need to be substituted. For consumer surplus, Eq. (37) still applies, but the equilibrium price p_1 must reflect the pricing behavior of oligopolistic RE producers. As before, consumer surplus declines significantly with risk aversion, particularly in concentrated markets. This is consistent with previous findings and reflects the pass-through of price increases to consumers.

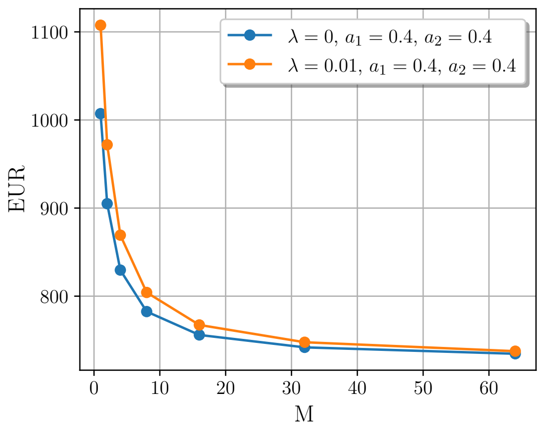
Likewise, the total welfare expression is the sum of the producer surplus of all market participants (oligopolistic RE producers, fringe RE producers, and conventional producers) and consumer surplus. By inserting the corresponding prices and quantities from this hybrid market structure, we obtain the welfare implications of strategic behavior under risk aversion in the presence of both competitive and dominant renewable producers. Figure 5 (d) shows that total welfare remains unchanged. This indicates that risk aversion primarily redistributes rents between producers and consumers, rather than generating allocative inefficiencies, if conventional producers are flexible.



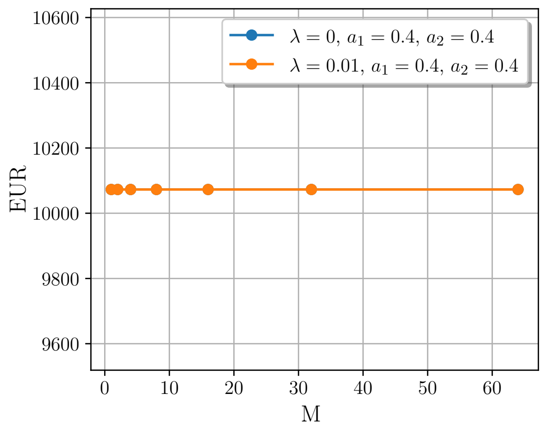
(a) RE producer surplus - oligopoly



(b) RE producer surplus - fringe



(c) Conventional producer surplus



(d) Welfare

Figure 5: Results under risk aversion, fexible supply curve and heterogenious RE producer: producer surplus, consumer surplus, and welfare

Note: M is the number of oligopolistic RE producers. λ is the coefficient of risk aversion. Results for an example with $a_1 = a_2 = 0.4$, $b = 20$, $d = 100$, $p_{VOLL} = 120$, $\mu_Q = 40$ and $\sigma_Q = 6$.

4. Discussion

This paper contributes to the literature on sequential electricity markets by introducing risk-averse behavior into an analytical framework of strategic bidding. While previous studies, such as Ito and Reguant (2016), emphasize the role of market power and limited arbitrage in generating forward price premia, they abstract from producers risk preferences. We contribute by explicitly modeling how risk aversion affects market outcomes under flexible and inflexible supply. In addition, we extend the framework by distinguishing between oligopolistic and competitive renewable producers, capturing a more realistic market structure. Our findings show that risk aversion, particularly under conditions of limited intraday flexibility, can magnify both price distortions and welfare losses, offering new insights into the interaction between market power, flexibility, and risk aversion.

A central finding is that risk aversion and concentrated markets lead to substantial welfare losses if intraday-markets are inflexible, represented by a steeper marginal cost curve. An inflexible intraday-market mirrors more realistic conditions, where conventional producers often lack the ability to adjust generation on short notice without incurring significant costs. This provides a further rationale for policy efforts aimed at improving short-term responsiveness through investments in storage, demand-side management, and flexible backup generation.

Our results further show that risk-averse producers strategically withhold more in the day-ahead market, driving up day-ahead prices and forward premia. While this effect vanishes under perfect competition, it becomes particularly problematic in oligopolistic markets with limited flexibility, amplifying price distortions and welfare losses. The interaction between risk aversion and market power suggests the need for closer examination of dominant producers' bidding behavior.

Beyond overall welfare, our results highlight important distributional implications. Strategic withholding increases producer surplus while reducing consumer surplus. Fringe renewable producers passively benefit from the market power of oligopolistic producers, with this effect becoming more pronounced under risk aversion. In the German regulatory setting, TSO's bidding rationale mimics the behavior of fringe RE producers. If TSOs were to behave oligopolistically, they could increase fringe's surplus, translating into lower subsidy costs, while consumer surplus would derease. If conventional production is inflexible ($a_2 > a_1$), overall welfare would decline if

TSOs bid strategically as seen in Case 2. Further research could investigate a welfare maximizing behaviour of TSOs, which would require an alternative formulation of the utility function.

This analysis omits a potential Case 4, which would combine conventional producer inflexibility with RE producer heterogeniety. Since the fringe bid the expected production in the first stage, Case 2 can be adjusted analogously to the shift in residual demand in Case 3. Thus, the main effects of Cases 2 and 3 are jointly present: (i) a welfare loss due to $a2 > a1$ and strategic withholding, and (ii) an increase in rents for the fringe. However, the welfare loss found in Case 2 would, ceteris paribus, be reduced by the fringe's bidding behavior, as they reduce the amount that is strategically withheld in the first stage.

In sum, our findings show that market power, risk aversion, and flexibility constraints interact. A robust market design should jointly promote competition, reduce risk, and improve operational flexibility to ensure efficient and equitable electricity markets in a low-carbon future.

The role of short-term storage, such as batteries, is neglected in our analysis, as their inclusion would require intertemporal linking across hours, substantially increasing the complexity of the model. Assessing the impact of batteries on our results is challenging, since they can arbitrage price differences both within a market (e.g., the day-ahead price spread from morning peaks to midday troughs) and across markets (e.g., from the day-ahead price at 7 a.m. to the Intraday price at 7 a.m.). If battery operators anticipate oligopolistic and risk-averse bidding behavior of RE producers, they could take physical positions to arbitrage the positions of these producers, selling in the day-ahead market and repurchasing quantities in the Intraday market. Such operations could mitigate the emergence of price premia. Moreover, if conventional production is inflexible, the activity of batteries could result in an overall welfare gain.

Several limitations must be considered when interpreting the results obtained in this study. We model risk aversion using profit variance, which is a simplification. While CVaR may better capture tail risks, it is analytically intractable in our setting. However, numerical results suggest profit variance remains a reasonable proxy for capturing aversion against uncertainty. Further, the model adopts a simplified structure to facilitate analytical tractability: it assumes linear costs, normally distributed uncertainty, and inelastic demand. While real-world cost curves are typically monotonically increasing and often approximated by convex functions, the assumption of linearity, following Knaut and Obermüller (2016), simplifies the analytical model. In principle, our results could be extended to convex cost functions, though this would significantly increase complexity.

A promising avenue for future research would involve an empirical examination of the analytical model. However, this is non-trivial, as empirically identifying risk aversion remains challenging given that it is not directly observable. Moreover, this would require disaggregating the withholding effect by market power and risk aversion. As capital-intensive, low-operating-cost technologies like renewables increasingly replace conventional power plants, understanding price formation and risk allocation in sequential electricity markets will become more critical.

5. Conclusion

This paper investigates the effects of risk aversion on market outcomes in sequential electricity markets, particularly focusing on the interaction between market power, flexibility, market structure, and producers' risk preferences. Our analytical framework builds upon Ito and Reguant (2016) and Knaut and Obermüller (2016), and is extended by incorporating risk-averse bidding behaviour. We focus on strategic bidding of RE producers who face uncertainty about their production in the first stage, which must be sold completely in the second stage. We assume perfect competition among conventional producers that form a linear marginal cost curve.

We demonstrate that in an oligopolistic setting, risk-averse RE producers tend to withhold more in the first stage of the market in order to hedge against profit risk. This behavior leads to an additional forward premium, which is absent in perfectly competitive markets, where risk aversion has no effect. Moreover, the forward premium increases with the degree of risk aversion, particularly when demand is sufficiently high relative to expected RE generation. The impact of risk aversion on the premium is further amplified by the slope of the second-stage supply curve: higher inflexibility in the second stage results in a larger forward premium.

When conventional producers have limited flexibility, risk-averse behavior in oligopolistic markets leads to additional welfare losses. Furthermore, fringe RE producers benefit from the market power of oligopolistic producers, with this effect becoming more pronounced when oligopolistic producers are risk-averse.

Beyond aggregate welfare effects, our analysis reveals important distributional implications. Strategic withholding not only increases the surplus of producers, both oligopolistic and competitive, but it also reduces consumer surplus, leading to higher prices for consumers. These findings underscore the need for careful market design that promotes competition and enhances system flexibility. In a future with increasing renewable energy penetration, ensuring efficiency in electricity markets will require addressing these interactions between market power, risk aversion, and flexibility.

Acknowledgements

The authors would like to thank Marc Oliver Bettzüge, Félix Michelet and Samir Jeddi for thoughtful and constructive comments and discussions on this work. This work also benefited from discussions at the 36th Young Energy Economists and Engineers Seminar (YEEES), organized by the University of Cologne.

Julian Keutz conducted this work in the framework of the Hans-Ertel-Centre for Weather Research funded by the German Federal Ministry of Research, Technology and Space (BMFTR) (grant number 4823DWDP5A). Amir Ashour Novirdoust and Pia Hoffmann-Willers gratefully acknowledge financial support of the German Federal Ministry of Research, Technology and Space (BMFTR) within the Kopernikus-project 'New ENergy grid StructURes for the German Energiewende' (ENSURE) (grant number 03SFK1L0-3). In addition, Pia Hoffmann-Willers gratefully acknowledges financial support of the European Union's Horizon 2020 research and innovation programme through the MAGPIE project ('sMArt Green Ports as Integrated Efficient multimodal hubs'; Grant Agreement No. 101036594).

Declarations

Confict of interest: The authors have no relevant financial or non-financial interests to disclose.
Use of AI and AI-assisted technologies: During the preparation of this work the authors used ChatGPT to improve the clarity, grammar, and phrasing of the manuscript. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

Appendices

A. *Use of variance as a risk metric*

In the ex-post evaluation of profit risk, assuming normally distributed realizations of Q, we find that profit variance decreases under risk aversion (λ), as expected. While the conditional value at risk (CVaR) is often preferred for capturing tail risks in asymmetric distributions, it is analytically intractable in our setting.

Approximations based on higher moments (e.g., skewness or kurtosis) are also impractical, as they would involve solving high-degree expressions. Despite the asymmetry in profits, we therefore adopt variance as a risk proxy within the mean-variance utility framework.

This choice is supported by our simulation results, which show a strong inverse correlation between profit variance and CVaR (see Figure A.1 and Figure A.2). Since profits are strictly positive, a higher CVaR is favoured. A maximization of the CVaR corresponds to a maximization of the lowest profits to an alpha-quantile ($\alpha = 0.05$). Hence, reducing variance can be interpreted as a reasonable approximation of maximizing CVaR.

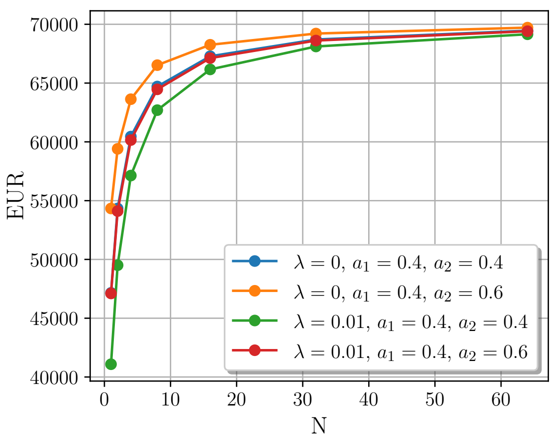


Figure A.1: Variance of RE producer profits

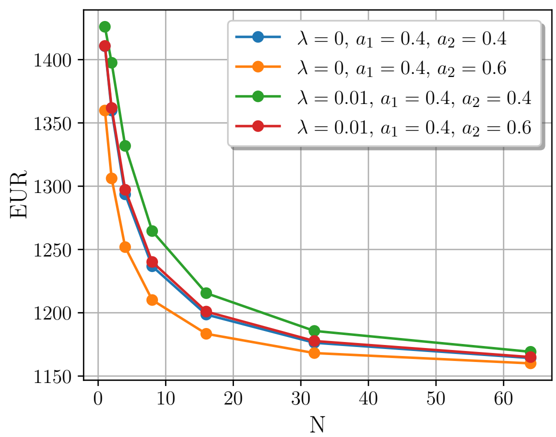


Figure A.2: Conditional Value at Risk of RE producer profits

B. *Choice of lambda*

To calibrate a reasonable value for the degree of risk aversion λ, we assume that a risk-averse RE producer is indifferent between a certain profit (π_{gi}) equal to the expected profit minus one standard deviation and the uncertain profit π_i. That is, the certainty equivalent is given by:

$$\pi_{gi} = \mathbb{E}[\pi_i] - \sigma_{\pi_i} = \mathbb{E}[\pi_i] - \frac{\lambda}{2} \cdot \mathrm{Var}(\pi_i) \tag{B.1}$$

Solving for λ gives:

$$\lambda = \frac{2 \cdot \sigma_{\pi_i}}{\mathrm{Var}(\pi_i)} \tag{B.2}$$

Using this method and the numerical assumptions from Table 2, we derive the following estimates: For a monopolistic setting ($N = 1$), we obtain $\mathbb{E}[\pi] = 1910$, $\mathrm{Var}(\pi) = 32{,}658$, and $\sigma(\pi) = 180.3$. This results in $\lambda_1 \approx 0.011$.

For a more competitive market ($N = 64$), we find $\mathbb{E}[\pi] = 1760$, $\mathrm{Var}(\pi) = 48{,}145$, and $\sigma(\pi) = 219.4$. Accordingly, $\lambda_{64} \approx 0.0091$.

While the precise value of λ plays a secondary role in our analysis, mainly serving for the visualization of effects, we choose $\lambda = 0.01$ as a consistent and reasonable estimate across different market settings.

C. Proof of Proposition 2

The profit function of a RE producer in our theoretical model framework for different marginal cost functions is described in Eq. (3). The first derivative results in:

$$\frac{d\mathbb{U}}{dq_{i1}} = \frac{d\mathbb{E}(\mathrm{profit})}{dq_{i1}} - \frac{\lambda}{2}\frac{d\mathrm{Var}(\mathrm{profit})}{dq_{i1}} \tag{C.3}$$

with

$$\frac{d\mathbb{E}(\mathrm{profit})}{dq_{i1}} = \mu_{Q_i}\,N\,a_2 - \mu_{Q_i}\,a + \mu_{Q_i}\,a_2 - N\,a_2\,q_{j1} - 2\,a_2\,q_{i1} + a_2\,q_{j1} \tag{C.4}$$

and

$$\begin{aligned}\frac{d\mathrm{Var}(\mathrm{profit})}{dq_{i1}} = \; & 2\,\sigma_{Q_i}^2\Big(-2\,\mu_{Q_i} N^2 a_2^2 + 2\,\mu_{Q_i} N\,a\,a_2 - 2\,\mu_{Q_i} N\,a_2^2 - N^2 a\,a_2\,q_{j1} \\ & + N^2 a_2^2\,q_{i1} + N^2 a_2^2\,q_{j1} + N\,a^2\,q_{j1} + N\,a\,a_2\,d - 2\,N\,a\,a_2\,q_{i1} - N\,a\,a_2\,q_{j1} \\ & + 2\,N\,a_2^2\,q_{i1} + N\,a_2\,b - a^2\,d + a^2\,q_{i1} - a^2\,q_{j1} + a\,a_2\,d - 2\,a\,a_2\,q_{i1} \\ & + 2\,a\,a_2\,q_{j1} - a\,b + a_2^2\,q_{i1} - a_2^2\,q_{j1} + a_2\,b\Big)\end{aligned} \tag{C.5}$$

Setting the derivative of Ui to zero and solving for q_{i1}^* results in the profit maximizing first-stage bid of RE producer i:

$$q_{i1}^* = \frac{\begin{aligned} &2\,\mu_{Q_i} N^2 \sigma_{Q_i}^2 a_2^2 \lambda - 2\,\mu_{Q_i} N \sigma_{Q_i}^2 a\, a_2 \lambda \\ &+ 2\,\mu_{Q_i} N \sigma_{Q_i}^2 a_2^2 \lambda + \mu_{Q_i} N\, a_2 - \mu_{Q_i} a \\ &+ \mu_{Q_i} a_2 + N^2 \sigma_{Q_i}^2 a\, a_2 \lambda\, q_{j1} - N^2 \sigma_{Q_i}^2 a_2^2 \lambda\, q_{j1} \\ &- N \sigma_{Q_i}^2 a^2 \lambda\, q_{j1} - N \sigma_{Q_i}^2 a\, a_2\, d\, \lambda + N \sigma_{Q_i}^2 a\, a_2 \lambda\, q_{j1} \\ &- N \sigma_{Q_i}^2 a_2\, b\, \lambda - N\, a_2\, q_{j1} + \sigma_{Q_i}^2 a^2\, d\, \lambda \end{aligned}}{\begin{aligned} &N^2 \sigma_{Q_i}^2 a_2^2 \lambda - 2\, N \sigma_{Q_i}^2 a\, a_2 \lambda + 2\, N \sigma_{Q_i}^2 a_2^2 \lambda \\ &+ \sigma_{Q_i}^2 a^2 \lambda - 2\, \sigma_{Q_i}^2 a\, a_2 \lambda + \sigma_{Q_i}^2 a_2^2 \lambda + 2\, a_2 \end{aligned}} + \frac{\begin{aligned} &\sigma_{Q_i}^2 a^2 \lambda\, q_{j1} - \sigma_{Q_i}^2 a\, a_2\, d\, \lambda - 2\, \sigma_{Q_i}^2 a\, a_2 \lambda\, q_{j1} \\ &+ \sigma_{Q_i}^2 a\, b\, \lambda + \sigma_{Q_i}^2 a_2^2 \lambda\, q_{j1} - \sigma_{Q_i}^2 a_2\, b\, \lambda + a_2\, q_{j1} \end{aligned}}{\begin{aligned} &N^2 \sigma_{Q_i}^2 a_2^2 \lambda - 2\, N \sigma_{Q_i}^2 a\, a_2 \lambda + 2\, N \sigma_{Q_i}^2 a_2^2 \lambda \\ &+ \sigma_{Q_i}^2 a^2 \lambda - 2\, \sigma_{Q_i}^2 a\, a_2 \lambda + \sigma_{Q_i}^2 a_2^2 \lambda + 2\, a_2 \end{aligned}} \tag{C.6}$$

Apply symmetry assumption $q_{i1} = q_{j1}$, $\mu_Q = \mu_{Qi} * N$, and $\sigma_Q = \sigma_{Qi} * N$ and solve for q_{i1}^*:

$$q_{i1}^* = \frac{A + \lambda B}{C + \lambda D} \tag{C.7}$$

where the components are defined as follows:

$$\begin{aligned} A &= \mu_Q N (N a_2 + a_2 - a_1) \\ B &= \sigma_Q^2 \Big(2\mu_Q N a_2^2 - 2\mu_Q a_1 a_2 + 2\mu_Q a_2^2 - N a_1 d a_2 - N b a_2 + a_1^2 d + a_1 b - a_1 d a_2 - b a_2 \Big) \\ C &= N (N^2 a_2 + N a_2) \\ D &= N \Big(\sigma_Q^2 \Big(-N a_1 a_2 + 2 N a_2^2 + a_1^2 - 3 a_1 a_2 + 2 a_2^2 \Big) \Big) \end{aligned}$$

D. *Proof Corollary 2*

In the following, we reformulate $\frac{dq_{i1}^*}{d\lambda} = \frac{BC - AD}{(2a_2 + \lambda D)^2}$ to prove Corollary 2. The numerator of Eq. (23) is:

$$BC - AD = \sigma_Q^2 \Big[2a_2 \Big(\mu_Q (4a_2^2 - 2a_1 a_2) + (-2a_1 d a_2 - 2b a_2 + a_1^2 d + a_1 b) \Big) - \mu_Q (2a_2 - a_1)(2a_2 - a_1)^2 \Big].$$

Reformulate to:

$$BC - AD = \sigma_Q^2 \cdot (a_1 - 2a_2) \Big(a_1 (a_1 - 4a_2) \mu_Q + 2a_2 (a_1 d + b) \Big).$$

Since $\sigma_Q^2 > 0$, $BC - AD < 0$ is equivalent to:

$$(a_1 - 2a_2)\Big(a_1(a_1 - 4a_2)\mu_Q + 2a_2(a_1 d + b)\Big) < 0$$

Reformulate to:

$$a_1(a_1 - 4a_2)\mu_Q > -2a_2(a_1 d + b),$$

Solve for μ_Q:

$$\mu_Q < \frac{2a_2(a_1 d + b)}{a_1(4a_2 - a_1)}.$$

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