Electric Power Systems Research 210 (2022) 108082

Contents lists available at ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr

Comparative analysis of risk-aversion and strategic investment behavior in generation expansion

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ARTICLE INFO

Keywords:
Alternating direction method of multipliers
Capacity markets
Elastic demand
Market equilibrium
Power system economics

ABSTRACT

Both risk-averse behavior and strategic bidding may distort the outcome of energy and capacity markets. Although these two behavioral aspects may trigger similar bidding behavior and investments into generation capacity, they are fundamentally different.

While in the literature risk-aversion and strategic behavior have been investigated separately, the presented research offers a comparative analysis to identify situations in which both types of behavior result in the same outcome. First, a framework is introduced in which both strategic and risk-averse behavior can be investigated for a generation expansion planning problem. The problem including the risk-averse investor is modeled as a Nash-equilibrium problem and solved via Alternating Direction Method of Multipliers, whereas the Stackelberg game between the strategic agent and the markets is formulated as a bi-level optimization problem and solved using disjunctive constraints.

Using a set of 1920 problem instances we reveal that the distinguishability of the two types of behavior is highly technology-dependent and influenced by the way the capacity target is set. Implications of this work may support regulators in disentangling risk-aversion and strategic behavior based on observed market outcomes.

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https://doi.org/10.1016/j.epsr.2022.108082
Received 1 December 2021; Received in revised form 25 February 2022; Accepted 7 May 2022
Available online 19 May 2022

Nomenclature

Abbreviations		
cm	Capacity market	
em	Energy market	
Expressions		
CVAR	Conditional-value-at-risk	€
$\mathbb{E}[\cdot]$	Expected value ($\mathbb{E}[x] = \sum_s \mathrm{P}_s x_s$)	
S	Surplus	€
Indices		
a	Risk-averse agent	
co	Consuming agent	
-i	Perfectly competitive agent	
i	Strategic agent	
s	Scenario	
t	Time step	
Market prices		
λ^{cm}	Capacity price	€/MW
λ^{em}	Energy price	€/MWh
Primal variables		
α	Value at risk (VAR)	€
$C_{\mathrm{i}}^{\mathrm{I,bid}}$	Capacity bid of the strategic agent	€/MW
e	Generated electricity	MW
e^{ela}	Energy consumption (elastic part)	MW
e^{VOLL}	Energy consumption (inelastic part)	MW
G_{i}	Dispatched capacity of the strategic investor	MW
u	Profit above VAR	€
y	Installed capacity	MW
Parameter		
A^{cm}	Derating factor for capacity	-
A^{e}	Availability factor for electricity	-
β	Risk-aversion factor, $\beta \in [0,1]$	-
C^{I}	Capital expenditures	€/MW
$\mathrm{D}_{\mathrm{e}}^{\mathrm{ela}}$	Total elastic share of demand	MW
$\overline{\mathrm{D}}_{\mathrm{e}}$	Electricity demand cap	MW
D_{cm}	Inelastic capacity demand	MW
γ	Weight of expected surplus, $\gamma \in [0,1]$	-
C^{OP}	Operating expenses	€/MWh
P	Probability	-
VOLL	Value of loss load	€/MWh
W	Weight of timestep	h

1. Introduction

In theory, capacity markets deliver the socially optimal capacity mix, if the capacity target is set optimally and investors are perfectly rational [1]. However, in reality, several factors exist which may cause the investment equilibrium to be different from the social optimum [2]. Among those, risk-averse behavior and strategic behavior received considerable attention. While risk-averse investors evaluate risks on e.g.

regulation, demand, fuel prices, or renewable penetration differently from perfectly rational agents [3,4], strategic investors, on the other hand, abuse their market power, e.g. via price bid markups or capacity withholding.

Acting strategically is sanctioned by regulators while acting risk-averse is tolerated and connected to the investors' risk attitudes.

It has been shown that risk-aversion and strategic behavior trigger fewer investments, raising the question of whether both behavioral aspects can lead to similar investments, and under which circumstances a distinction can be made between these behaviors. Having access to less information than the market participants under investigation, disentangling these effects is a challenging task for regulators.

There is a real-life concern regarding risk-averse or strategic behavior that is shared by authorities worrying about negative impacts on the performance of the electricity system. The Belgian TSO, Elia, states that the power generation industry is confronted with higher capital costs since capital markets are risk-averse [5] and ENTSO-E reports inadequate expected revenues to reflect investors' risk perception [6]. In the European Resource Adequacy Assessment (ERAA), ACER prescribes to use the value-at-risk to take the consequences of risk-aversion into account if forward products are unavailable [7]. To counteract strategic behavior, the design of a capacity market that is resilient against strategic abuse is subject to ongoing discussions, e.g. in the Belgian market [8]. Similarly, in the United States it has been acknowledged that market power was abused in the capacity markets in the form of capacity withholding (New England and Colombia [9]). Moreover, the court case FERC vs. PJM on market power review and mitigation in PJM's capacity market highlights the relevance of possible market power abuse [10].

Being of interest to authorities, both risk-averse and strategic behavior received considerable attention in the scientific literature. The effect of risk-aversion on investment decisions has been investigated in several modeling frameworks using stochastic generation expansion models [3,11], system dynamics models [12], or by solving stochastic generation expansion models by iterative approaches [13,14]. The conducted studies observed a tilt of the generation mix towards less capital-intensive technologies if investors are risk-averse. Similarly, another stream of the scientific literature has extensively targeted the topic of strategic behavior. While the majority of the approaches focus on strategic bidding and dispatch decisions, few works consider strategic abuse of market power on the investment stage (e.g. [15,16]). An overview of various bi-level programming approaches can be found in the work of Kazempour et al. [17]. Recent studies also connect capacity markets with the possibility of market power abuse using a two-stage game for different market designs [18], comparing reliability options or financial obligations with other capacity market designs [19,20], or focusing on the Irish market [21].

To our knowledge, the literature has focused either on risk-aversion or on strategic behavior, while in real-world applications both behavioral aspects can occur and may be difficult to disentangle as they may lead to similar market outcomes and investment decisions [22].

Therefore, a framework is developed that highlights ex-post market outcomes, i.e. installed capacity and capacity market prices, to disentangle risk-aversion and strategic power abuse in the investment stage, which may support regulators in distinguishing risk-aversion and strategic behavior. Our goal is to shed light on situations when the two behaviors may overlap, but also when they can be distinguished. Strategic and risk-averse behaviors are reflected in a single model with identical inputs. Strategic behavior is mimicked by formulating a bi-level generation-expansion problem (Stackelberg game). Risk-averse behavior is modeled in a single agent using the Conditional-Value-at-Risk (CVAR). The corresponding Nash-game is formulated as an equilibrium problem reflecting agents with inhomogeneous risk attitudes.

The main contribution of this work is the design of a framework that allows comparing risk-averse and strategic investment behavior. Therefore, a generation expansion problem is synthesized by combining elements from literature to model strategic and risk-averse behavior on an energy-only market complemented with a capacity market. We extend the models in literature by reflecting asymmetric risk attitudes, as well as investment decisions and capacity markets on the lower-level of the Stackelberg game. To solve the resulting mathematical optimization problems, we apply the Fortuny-Amat reformulation, and Alternating Direction Method of Multipliers (ADMM) for the Stackelberg game or the Nash game.

In a numerical case study, we consider either risk-averse or strategic behavior for different generation technologies, namely base-, mid-, and peak-load technologies. Our numerical results show that cases exist, where both behaviors lead to identical market outcomes, and thus, resemble each other. Using a large set of instances, we show that for base-load technology in an energy-only market, risk-aversion is not likely to be mixed up with strategic behavior. On the other hand, for mid,- and peak-load technologies we show that identical market outcomes can occur. In these cases, the degree of risk-aversion positively correlates with the investment cost of the considered technology. In contrast, we identify that capacity targets set to the peak-load allow distinguishing between risk-averse and strategic behavior.

The remainder of this paper is structured as follows. Sections 2.1 and 2.2 introduce the games including a strategic and a risk-averse investor. Solution methods are explained in Sections 2.3. The comparative case study is presented in Sections 3. Sections 4 concludes this work.

2. Methodology

Strategic and risk-averse behavior is formulated in the same modeling framework. We consider four types of agents: a strategic investor, a risk-averse investor, a perfectly competitive fringe, and a demand agent. To formulate the decision problem of the strategic agent, we employ bi-level programming to resemble the underlying Stackelberg game. To characterize risk-aversion, the Conditional-Value-At-Risk (CVAR) is used as a risk metric of the risk-averse agent. The risk-averse game, involving the risk-averse agent, the perfectly competitive fringe, and the demand agent, forms a Nash-equilibrium problem. In both games, the strategic and the risk-averse investor decide on capacity investments and the bids sent to the energy and the capacity market.

The presented study provides a stylized model framework focusing on the most relevant aspects of risk-aversion and strategic power abuse. Hence, the generation-expansion-problem (GEP) is formulated as a green-field study, i.e. assuming that there is no pre-existing legacy capacity, and transmission and distribution grid constraints are not considered. By limiting every investor to be responsible for a single technology we enforce that risk can only be hedged on the considered markets and not by altering investment portfolios. While on the energy market a large number of competitors submit bids, the number of competitors on the capacity market is comparably lower, and information about the composition of the price of the capacity bid is generally not publicly available. Therefore, detecting market power abuse, exercised by manipulating the price component of the bid, is a challenging task for authorities. We reflect these characteristics in the bidding behavior of the strategic investor on the energy and the capacity market. For the energy market, price-quantity bids resemble the true marginal costs and available capacities. For the capacity market, strategic power can be exerted by placing strategic bids. Strategic bids are restricted to resemble the true installed capacity, while the price component of the capacity bid can be chosen freely and, therefore, could also even exceed the costs for installing capacity. The strategic investor can decide on the amount of installed capacity and increase market prices by installing less capacity. Such situations can occur, if e.g., the number and the access to feasible locations for power plants is limited, market entrance barriers for large investments exist, or if the transmission is limited by existing transmission lines [23].

The impact of risk-aversion depends on the ability to trade risk by capacity markets or financial long-term products. If the markets were

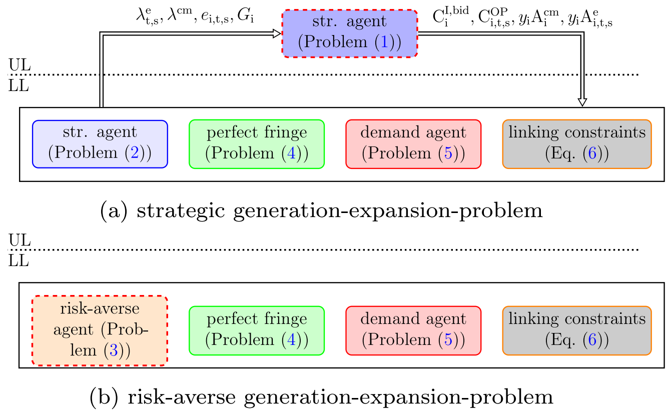

Fig. 1. Overview of games.

complete, i.e. financial risks are perfectly hedged, a (risk-aware) social optimum would be obtained [11,24]. However, empirical evidence suggests that real-world markets are far from complete [25] as forward markets usually do not hedge energy prices for longer than three years, which is comparatively shorter than the time needed for recovering the investment cost [26].

Likewise, if policies and regulations were perfect, strategic opportunities would not exist. Assessing the likeliness of situations that allow strategic leverage on the investment level or the degree of market completeness and level of risk-aversion constitute interesting strains of research. However, this work focuses on showing the impacts of strategic behavior and risk aversion and their resemblance given the described modeling assumptions.

In Sections 2.1 we highlight the composition of the Stackelberg game and the Nash-equilibrium problem. Subsequently, we introduce the agents' problems used in the games (Sections 2.2). Eventually, we present the used solution strategies in Sections 2.3.

2.1. Formulation of strategic and risk-averse games

To set up the Stackelberg game (strategic GEP) and the Nash-equilibrium (risk-averse GEP) the agents' problems need to be initialized and connected. Fig. 1 provides a graphical overview of the structure in both games.

2.1.1. Strategic investment planning model

We model the Stackelberg game as a bi-level problem. The upper level (UL) contains the profit maximization problem of the strategic agent. The lower level (LL) reflects the equilibrium problem between the market participants. The exchange of information between the upper and lower level problem is highlighted in Fig. 1. The upper-level agent submits price-quantity bids to the energy ($C^{OP}_{i,t,s}, y_i A^{e}_{i,t,s}$) and the capacity market ($C^{I,bid}_i, y_i A^{cm}_i$) on the lower level while taking the lower levels dispatch ($e_{i,t,s}, G_i$) and price information ($\lambda^{e}_{t,s}, \lambda^{cm}$) of both markets into account.

The lower level problem describes an equilibrium problem between the dispatch decisions of the strategic Generation Company (GenCo) and the perfectly competitive fringe on the one side, and decisions of the consumer regarding capacity and energy on the other side.

2.1.2. Risk-averse investment planning model

The risk-averse investment planning problem is modeled as an equilibrium problem. In this setting, one risk-averse agent competes with the perfectly competitive, risk-neutral fringe, which is composed by perfectly competitive GenCos. The demand-side is again modeled using an aggregated energy and capacity consumer.

2.2. Agents' problems

2.2.1. Strategic investor

The strategic agent, i, strives to maximize its profit by deciding on strategic price-quantity bids and capacity investments. The strategic agent is presented to the other agents solely by its bids. Therefore, an optimization problem on the upper- and on the lower-level is necessary to describe its internal decision-making on the one hand, and its representation to the other agents on the other hand.

On the upper level, the strategic investor maximizes its expected profit ($\mathbb{E}[S_i]$) over all scenarios $s \in \mathscr{S}$. Uncertainty is introduced exogenously as described in Section 3.1. In the upper level problem, investments decisions (y_i), and price bids on the capacity market ($C^{I,bid}_i$) are made considering the generation and investment decisions of non-strategic agents indirectly and generation decisions on the energy market ($e_{i,t,s}$) and the capacity market (G_i) directly. To the energy market the strategic agent offers the price/quantity pair ($C^{OP}_{i,t,s} \big| y_i A^{e}_{i,t,s}$), to the capacity market it submits the pair ($C^{I,bid}_i \big| y_i A^{cm}_i$). As we do not consider strategic bidding on the energy market, bids that are submitted to the energy market are fixed to the real marginal production costs of the strategic agent ($C^{OP}_{i,t,s}$) and to the available installed capacity ($y_i A^{e}_{i,t,s}$). However, market power can be exerted via strategic investment decisions. On the capacity market, $C^{I,bid}_i$ is a free (and strategic) decision variable, while the quantity bid is forced to reflect the available capacity ($y_i A^{cm}_i$).

$$\min_{y_i, C^{I,bid}_i} -\mathbb{E}[S_i] = -\Big(\sum_{t,s} P_s W_t \left(\lambda^{e}_{t,s} - C^{OP}_{i,t,s}\right) e_{i,t,s} - y_i C^{I}_i + G_i A^{cm}_i \lambda^{cm}\Big) \quad \text{s.t.} \tag{1a}$$

$$-y_i \le 0 \tag{1b}$$

$$-C^{I,bid}_i \le 0 \tag{1c}$$

$$\lambda^{e}_{t,s}, \lambda^{cm}, e_{i,t,s}, G_i \in \arg\min\{LL\} \tag{1d}$$

The expected profit of the strategic agent is the difference between revenues from the energy market ($\lambda^{e}_{t,s} e_{i,t,s}$) and from the capacity market ($G_i A^{cm}_i \lambda^{cm}$) and costs of producing electricity ($C^{OP}_{i,t,s} e_{i,t,s}$) and installing capacity ($y_i C^{I}_i$). The accepted bid on the energy market and the amount of capacity contracted on the capacity market is determined by the lower-level optimization as described below. A^{cm}_i is the capacity factor, that describes the available capacity (for the capacity market) as a fraction of the installed capacity. The length of a time step is indicated with W_t and the probability of a scenario with P_s.

In the lower-level optimization problem, profits are maximized as well. However, in this representation of the strategic agent to the LL, the bids of the UL are taken into account:

$$\min_{e_{i,t,s}, G_i} -\sum_{t,s} P_s W_t \left(\lambda^{e}_{t,s} - C^{OP}_{i,t,s}\right) e_{i,t,s} - G_i \left(A^{cm}_i \lambda^{cm} - C^{I,bid}_i\right) \quad \text{s.t.} \tag{2a}$$

$$0 \le e_{i,t,s} \le y_i A^{e}_{i,t,s} \left(\underline{\Delta}^{e}_{i,t,s}, \overline{\Delta}^{e}_{i,t,s}\right), \forall t, s \tag{2b}$$

$$0 \le G_i \le y_i A^{cm}_i . \left(\underline{\Delta}^{cm}_i, \overline{\Delta}^{cm}_i\right) \tag{2c}$$

Here, the expected surplus is defined as infra-marginal profits between market prices and price bids. The dispatched quantities on the energy ($e_{i,t,s}$) and capacity market (G_i) are limited by the offers decided on the upper level, which are fixed to the installed and available capacity. $A^{e}_{i,t,s}$ describes the availability factor.

2.2.2. Risk-averse investor

Risk aversion (RA) is modeled using the Conditional-Value-At-Risk (CVAR) that considers the β-proportion of worst-case scenarios [27]. The objective function of the risk-averse investor is the sum of a γ-weighted expected surplus and $(\gamma-1)$-weighted CVAR. The set of decision variables is indicated with $\Xi_a = \{e_{a,t,s}, y_a, u_{a,s}, \alpha_a\}$. The optimization problem of risk-averse agent, a, formalizes to:

$$\min_{\Xi_a} -\gamma\sum_s P_s S_s - (1-\gamma)\mathrm{CVAR}_a \tag{3a}$$

with

$$S_s = \sum_{t,s} W_t\left(\lambda^{e}_{t,s} - C^{OP}_{a,t,s}\right)e_{a,t,s} + y_a\left(A^{cm}_a\lambda^{cm} - C^{I}_a\right) \tag{3b}$$

$$\mathrm{CVAR}_a(\Xi_a) = \alpha_a - \frac{1}{\beta}\sum_s P_s u_{a,s} \tag{3c}$$

s.t.

$$\alpha_a - S_s \le u_{a,s} \quad \forall s \tag{3d}$$

$$0 \le e_{a,t,s} \le y_a A^{e}_{a,t,s} \forall t,s \tag{3e}$$

$$0 \le y_a \tag{3f}$$

$$0 \le u_{a,s} \forall s \tag{3g}$$

$$\alpha_a \in \mathbb{R}. \tag{3h}$$

The surplus of the risk-averse investor is calculated as the inframarginal rents on the energy (Eq. (3b), first line) and the capacity market (Eq. (3b), second line). The price-quantity bids of the risk-averse investor are implicitly chosen to $(C^{OP}_{a,t,s}|e_{a,t,s})$ for the energy and $(C^{I}_a|y_a)$ for the capacity market. Hence, the risk-averse investor bids at marginal costs for generating electricity and procuring capacity.

2.2.3. Perfect GenCo

The perfectly competitive fringe consist of perfectly competitive risk-neutral GenCos. Similar to the risk-averse agent, the perfect, price-taking GenCo is assumed to offer its full capacity to the energy and the capacity markets at its true marginal costs. As previously presented, the expected surplus is maximized. The generation expansion problem of the price-taking GenCo, $-i$, reads as:

$$\min_{e_{-i,t,s}, y_{-i}} -\mathbb{E}[S_{-i}] = -\sum_{t,s} P_s W_t\left(\lambda^{e}_{t,s} - C^{OP}_{-i,t,s}\right)e_{-i,t,s} + y_{-i}\left(C^{I}_{-i} - A^{cm}_{-i}\lambda^{cm}\right) \tag{4a}$$

s.t.

$$0 \le e_{-i,t,s} \le y_{-i}A^{e}_{-i,t,s}\left(\underline{\delta}^{e}_{-i,t,s}, \overline{\delta}^{e}_{-i,t,s}\right), \forall -i,t,s \tag{4b}$$

$$0 \le y_{-i}(\overline{\delta}^{cap}_{-i}), \forall -i. \tag{4c}$$

2.2.4. Energy consumer

The formulation of the energy consumer's problem is taken from Kaminski et al. [1]. The energy consumer's surplus is modeled as the difference between Willingness-To-Pay (WTP) and the clearing price on the energy market. We assume a sloped WTP function that is capped at the Value-Of-Lost-Load (VOLL). The slope of the WTP function is parameterized by the amount of elastic demand in the system (D^{ela}_e) and consumption at a price of 0€ /MWh ($\overline{D}_{e,t,s}$).

$$\min_{e^{VOLL}_{co,t,s}, e^{ela}_{co,t,s}} \sum_{t,s} P_s W_t\left(\left(e^{VOLL}_{co,t,s} + e^{ela}_{co,t,s}\right)\cdot\left(-\mathrm{VOLL} + \lambda^{e}_{t,s}\right) + \left(e^{ela}_{co,t,s}\right)^2 \cdot \frac{\mathrm{VOLL}}{2\cdot D^{ela}_e}\right) \tag{5a}$$

s.t.

$$0 \le e^{VOLL}_{co,t,s} \le \overline{D}_{e,t,s} - D^{ela}_e\left(\underline{\mu}^{cap}_{t,s}, \overline{\mu}^{cap}_{t,s}\right), \forall t,s \tag{5b}$$

$$0 \le e^{ela}_{co,t,s} \le D^{ela}_e\left(\underline{\mu}^{ela}_{t,s}, \overline{\mu}^{ela}_{t,s}\right), \forall t,s \tag{5c}$$

2.2.5. Linking constraints

The energy and capacity market are represented by the following linking constraints:

$$0 = W_t P_s\left(e^{VOLL}_{co,t,s} + e^{ela}_{co,t,s} - e_{i/a,t,s}\cdot \cdot - \sum_{-i} e_{-i,t,s}\right) \quad \left(\lambda^{e}_{t,s}\right) \quad \forall t,s \tag{6a}$$

$$0 \ge D_{cm} - G_i A^{cm}_i - \sum_{-i} y_{-i}A^{cm}_{-i}(\lambda^{cm}) \tag{6b}$$

The dual variables $\lambda^{e}_{t,s}$ and λ^{cm} can directly be interpreted as energy market and capacity market prices. If considering a risk-averse investor, the second term of the capacity market constraint, $G_i A^{cm}_i$, is substituted by $y_a A^{cm}_a$.

2.3. Solution strategies

2.3.1. Stackelberg game

The bi-level problem (Fig. 1(a)) is solved via reformulating the lower-lower problem, Eqs. (2.2.1) and (2.2.3)–(2.2.5), using its Karush-Kuhn-Tucker (KKT) conditions and imposing those as constraints of the upper-level problem, Eq. (2.2.1). This formulation leads to bilinear terms in both the objective function of the strategic agent and in the complementary slackness conditions of the LL problem which impose non-convexities to the problem [28]. To enable the solver to find optimal solutions, we reformulate the non-convexities.

The bi-linear terms in the objective Eq. (1a) describe revenues from the energy and capacity market. These terms are linearized as shown by, e.g., Dolanyi et al. [28] and Guo et al. [29] via utilizing the KKT conditions of the lower level problem. This linearization involves three steps: (1) inserting the energy and capacity balance into the left-hand side of Eq. (7), (2) multiplying the optimality conditions with the respective decision variable and inserting it into Eq. (7), and (3) insert the complementarity conditions for eliminating remaining bi-linear terms. The resulting equation is depicted in Eq. (7) describing the expected revenues of the energy market and the capacity market.

$$\begin{aligned}\sum_{t,s} W_t\cdot P_s\cdot\lambda^{e}_{t,s}e_{i,t,s} + G_i\cdot\lambda^{cm} = \\ \sum_{t,s}\left(W_t\cdot P_s\cdot \mathrm{VOLL}\cdot\left(e^{ela}_{co,t,s} - \left(e^{ela}_{co,t,s}\right)^2 \Big/ D^{ela}_e\right) - D^{ela}_e\cdot e^{ela}_{co,t,s}\right) \\ + \sum_{t,s}\left(W_t\cdot P_s\cdot \mathrm{VOLL}\cdot e^{VOLL}_{co,t,s} - \left(\overline{D}_{e,t,s} - D^{ela}_e\right)\cdot\overline{\mu}^{cap}_{t,s}\right) \\ + \lambda^{cm}\cdot D_{cm} \\ - \sum_{-i,t,s}\left(e_{-i,t,s}\cdot P_s\cdot W_t\cdot C^{OP}_{-i,t,s}\right) \\ - \sum_{-i,} C^{I}_{-i}\cdot y_{-i}\end{aligned} \tag{7}$$

The remaining bi-linear terms are part of the complementarity constraints. To linearize these, we use the formulation introduced by Fortuny-Amat and McCarl [30] using disjunctive constraints: a bilinear term, e.g. $g(x)\lambda$, can be linearized as

$$\lambda \leq zM, \tag{8}$$

$$g(x) \leq (1 - z)M, \tag{9}$$

where M is a sufficiently large positive number and z is a binary variable.

Consequently, the Stackelberg game is solved as a MILP. For the solution process, a relative MIP gap of 0.01 and primal, dual, and integer feasibility tolerance of 10^{-9} are used.

2.3.2. Risk-averse Nash-equilibrium

In principle, the risk-averse equilibrium problem is solvable via deriving the KKT conditions and applying a linearization for the complementarity conditions as presented by Fortuny-Amat and McCarl [30] or using, e.g., the PATH solver. However, the complementarity conditions of the CVAR impose additional nonlinearities [11] which are difficult to reformulate or may render the resulting problem intractable for dedicated solvers. Therefore, we use Alternating Direction Method of Multiplier (ADMM) as a solution method [13]. The convergence of the ADMM algorithm is not proven for this class of problems. However, it can be shown that if converged, the KKTs of the augmented problem coincides with the KKTs of formulations Eqs. (2.2.2), (2.2.3), and (2.2.4).

In this paper, we apply the ADMM algorithm as presented in Kaminski et al. [1]. In this context, the ADMM algorithm allows iteratively updating the agents' decisions and market prices according to the resulting market imbalances. If no agent deviates from its previous decisions given the market prices and market imbalances satisfy preset tolerances, the solution is accepted as a Nash equilibrium and the algorithm stops. The used primal and dual convergence tolerances are 5×10^{-4}, and the maximum number of iterations is 10^5.

2.3.3. Implementation and solver

All problems are implemented in Julia using the JuMP package and solved using Gurobi.

3. Case-study

We study risk-averse and strategic investment behavior by applying identical inputs to both problems. We vary the level of risk-aversion, from risk-neutral ($\beta = 1.0, \gamma = 1.0$) to entirely risk-averse ($\beta = 0.1, \gamma = 0.1$), and compare these outcomes to outcomes of games involving a strategic investor to conclude whether both behaviors can be mixed up and when they can be distinguished. As a benchmark, we use the outcome of a perfectly competitive (PC) game considering only rational and risk-neutral agents.

In this section, we first introduce the model inputs (Section 3.1). Then, results for an Energy-Only Market (EOM) (Section 3.2), and an energy market complemented with a capacity market (Section 3.3) are presented. Lastly, in Section 3.4, we test the sensitivity of the drawn conclusions by conducting simulations with a large set of instances with various input assumptions.

3.1. Definition of inputs

We consider data from the Belgian system in 2015, 2017, and 2019. Uncertainty solely is considered on the residual energy demand. We calculate the residual energy demand considering total load data and renewable load factors of Belgium from 2015, 2017, and 2019, installed renewable capacities of 2017 and 2019, and a profile with 20% increased capacities of 2019. The combination of these profiles leads to 27 residual load profiles which are used in the following studies.

Each profile is reduced to 20 periods using a representative period finder tool [31], which chooses optimal residual load slices with the corresponding duration for each of the 27 scenarios using an optimization procedure. Reduced profiles contain the original peak load hour. Combined, these scenarios form the uncertainty set for all optimization problems presented in the following sections.

Table 1
Reference technology parameters.

	GEN1	GEN2	GEN3
CAPEX in € /MW	200000	50000	35000
OPEX € /MWh	23	62	91

We consider three technologies that can be characterized as base-, mid-, and peak-load technologies. The technology parameters used are summarized in Table 1.

On the consumer side, we approximate the VOLL with 3000€ /MWh and the inelastic demand ($\overline{D}_{e,t,s}$) with the residual demand. For Sections 3.2 and 3.3 elastic demand (D_e^{ela}) in the system is assumed to be 500MW.

3.2. Comparing behaviors on energy-only market

Exemplary risk aversion (RA) parameters of $\beta = 0.2$ and $\gamma = 0.8$ ("sample") are considered and compared with strategic behavior (SB), perfect competition (PC), and the range of outcomes possible when behaving RA within $\gamma \in [0.1, 1]$ and $\beta \in [0.1, 1]$. Each optimization considers either one RA agent or one SB agent and the perfectly competitive fringe for the other two technologies. The RA or SB agent and its technology, e.g. GEN1, is abbreviated as *Imperfect-Technology-1, IT1*. To reflect an EOM, the capacity demand D_{cm} is set to zero in Eq. (6b).

The relationship between the different choices of the risk-aversion parameters (γ, β) and the installed capacity of the corresponding risk-averse agent are depicted in Fig. 2 (IT2) and in Fig. 3 (IT3). The varied metrics may be seen as a way of parameterizing the agent's risk-aversion. Both figures highlight the sensitivity of the installed capacities towards the degree of risk-aversion. For the highest considered risk-aversion, both technologies vanish completely from the generation mix. While GEN2 technology is reaching its minimum only in the case of $\gamma = \beta = 0.1$, GEN3 technology already leaves the generation mix with $\gamma = 0.75$ or $\beta = 0.9$ (see Fig. 3). In the following, the ranges of risk aversion ($\gamma \in [0.1, 1]$, $\beta \in [0.1, 1]$) are depicted using error bars.

Fig. 4 shows an overview of installed capacities for RA, SB and the perfectly competitive benchmark. Generally, it can be observed that RA/SB investors invest in less capacity than rational agents in the perfectly competitive benchmark. If technology GEN1 is used by the strategic or risk-averse agent (IT1), results show that the SB agent invests in less capacity than the RA agent regardless of the parameterization of the CVAR, while the perfectly competitive fringe compensates for the capacity deficit using technology GEN2. For the IT2 and IT3 cases, RA

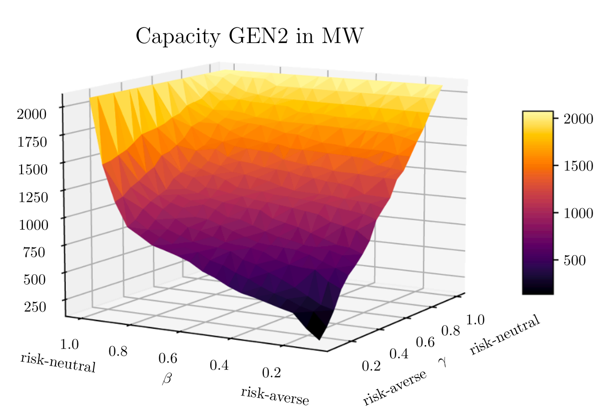

Fig. 2. Risk-averse capacity range of IT2 on EOM.

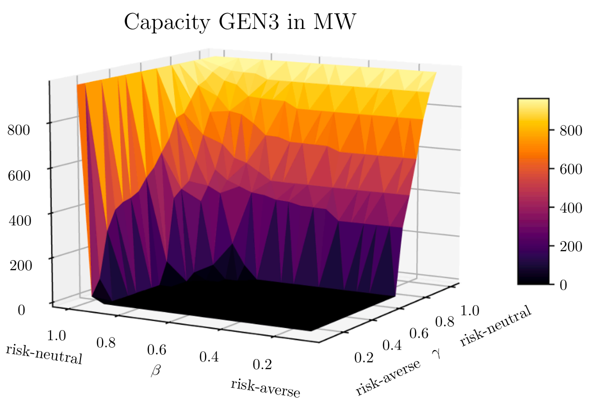

Fig. 3. Risk-averse capacity range of IT3 on EOM.

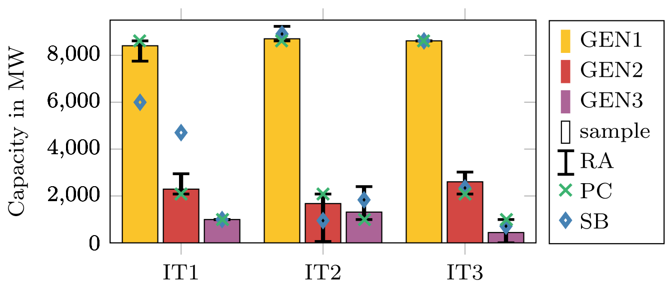

Fig. 4. Comparison of installed capacities on an EOM. Imperfect Technology (IT) indicates which technology is used by the either risk-averse (error bar, $\beta = 0.1, \gamma \in [0.1, 1]$) or strategic agent (diamond). Bars indicate a risk-averse sample with $\gamma = 0.8$ and $\beta = 0.2$. Perfect competition is indicated using the cross mark. The technology type is indicated by different colors.

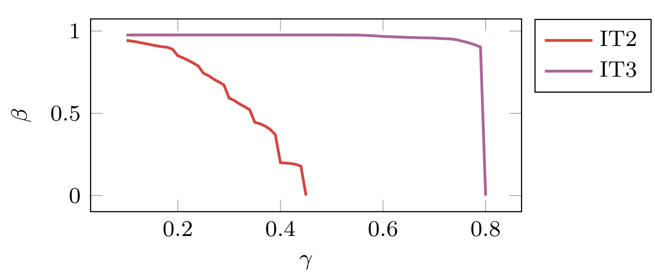

Fig. 5. Interpolated risk-aversion parameters at intersection with installed capacity of strategic agent. Imperfect Technology (IT) indicates which technology is used by the either the risk-averse or the strategic agent.

investment decreases to 0MW total installed capacity when risk-averse agents are highly risk-averse ($\gamma = \beta = 0.1$). Thus, a clear distinction between RA and SB cannot be made without further information about the degree of risk-aversion. The capacity deficits in GEN2 are compensated with GEN3 and vice-versa. The reader should note that not all missing capacity of GEN3 is compensated by GEN2.

Results show that installed capacities can give an indication for strategic investment and risk-aversion, while strategic behavior can clearly be separated with risk-aversion in case GEN1 technology is abused. However, this study reflects the theoretical optimum assuming that the strategic agent (i) has perfect foresight on the market and (ii) an optimistic response of the market w.r.t. the strategic agent's objective. These considerations may result in a more aggressive market abuse than what the agent would carry out in reality. As the degree of risk aversion is typically not known to a regulator, SB and RA cannot be distinguished for IT2 and IT3 in this context.

To investigate which degree of risk-aversion (pairs of γ and β) can lead to an identical market outcome as strategic investment behavior, we calculate where the installed capacity of the strategic investor equals the capacity of the risk-averse investor. The corresponding γ-β-pairs are illustrated in Fig. 5. Geometrically, we calculate the intersection of the horizontal plane representing the investment of a strategic investor (strategic investments are not dependent on risk aversion) with the surfaces as presented in Figs. 2 and 3. The capacity of the horizontal plane is equal to the values of the strategic investor as depicted in Fig. 4 (diamonds). In the comparison in Fig. 5 the intersections of the capacity of risk-averse investors and the strategic investor are illustrated, not intersections with the capacity of the perfectly competitive fringes.

For IT3 even a risk aversion of $\gamma \leq 0.8$ and $\beta \leq 0.97$ triggers the risk-averse agent to reduce its investment to a level that can be mixed up with SB, while for IT2 a higher degree of risk-aversion ($\gamma \leq 0.44$ and $\beta \leq 0.94$) leads to this result.

3.3. Comparing behaviors on energy and capacity market

The goal of this section is to assess how a complementary capacity market affects the conditions to distinguish between SB and RA. To disentangle the effects, we first present installed capacities (cf. Table 2) considering a complementary capacity market. In a second step, we consider the capacity market price as an additional observation to detect strategic power abuse (Fig. 6). In the numerical simulations, the capacity target is set in two ways. Either we set the capacity target equal to the installed capacity of a perfectly competitive energy-only market with rational agents, or we set the capacity target to the peak load. We refer to the former as *Social Optimal (SO)* target, while we refer as *Peak* to the latter. In Table 2, outcomes with risk-averse agents are limited by row $\overline{RA}$ reflecting the most risk-averse attitude ($\beta = \gamma = 0.1$) and PC reflecting risk-neutral agents.

We generally do not observe scarcity of capacity in the case of IT1 or IT2 (i.e., total installed capacity remains the same). In these cases, the perfectly competitive fringe invests in the missing capacity filling the

Table 2
Overview of installed capacities in MW for an energy-only market and a capacity market with a capacity target set to the social optimal (SO) capacity target, and to the peak-load.

		CM target											
		0.0 (EOM)				SO				Peak			
		GEN1	GEN2	GEN3	total	GEN1	GEN2	GEN3	total	GEN1	GEN2	GEN3	total
	PC	8615	2082	994	11691	8615	2082	994	11691	8615	2082	3162	13859
IT1	$\overline{RA}$	**7750**	2947	994	11691	**7750**	2947	994	11691	**8066**	2630	3162	13859
	SB	**5996**	4701	994	11691	**5996**	4701	994	11691	**5996**	4701	3162	13859
IT2	$\overline{RA}$	9234	**59**	2399	11691	9234	**59**	2399	11691	8726	**1548**	3586	13859
	SB	8908	**949**	1834	11691	8908	**949**	1834	11691	8908	**949**	4002	13859
IT3	$\overline{RA}$	8615	3019	**0**	11634	8615	3077	**0**	11691	8615	2082	**3162**	13859
	SB	8615	2342	**713**	11669	8615	2613	**464**	11691	8615	2987	**2258**	13859

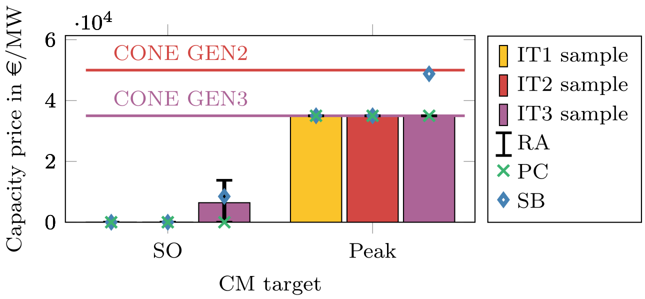

Fig. 6. Capacity market prices for a social optimal (SO) and peak-load capacity target. Imperfect Technology (IT) indicates which technology is used by the either risk-averse (error bar, $\beta = 0.1$, $\gamma \in [0.1, 1]$) or strategic agent (diamond). Bars indicate a risk-averse sample with $\gamma = 0.8$ and $\beta = 0.2$. Perfect competition (PC) is indicated using the cross mark. The technology type is indicated by different colors.

capacity gap introduced by RA or SB. This introduces additional costs which are recovered by raising the mean electricity price. In contrast, assuming situations in which the agent behaving imperfectly can invest in GEN3 could principally trigger capacity scarcity (from a social perspective). The needed investment costs for GEN1 and GEN2 cannot fully be recovered by scarcity pricing (Table 2, EOM rows). In that case, a capacity market can trigger investments.

For the socially optimal (SO) set capacity target, RA and SB can be clearly distinguished for IT1 (the capacity lies outside the interval spanned by $\overline{\text{RA}}$ and PC in Table 2). In contrast, for IT2 and IT3 the capacity of the strategic agent falls within the range spanned by PC and $\overline{\text{RA}}$. Thus, for IT2 and IT3 the distinction between risk-averse and strategic behavior cannot be made without knowing the true risk-parameters.

For the capacity target set to the peak load, a mix-up between RA and SB is not indicated by our results. Given the modeling assumptions, the SB agent is forced to offer all installed capacity to the capacity market, while the offer price is left to its choice. In the results, we observe that the risk-averse agent increases its investment while the strategic investor does not change its investment decisions comparing IT1 and IT2 of the SO target. Consequently, the capacity range of the RA investor moves to higher levels of capacity and does not intersect with the investment of the SB agent.

As described, taking installed capacity as the single indicator for imperfect behavior does not allow a clear disentanglement of RA and SB. Thus, we introduce the capacity market prices as a second indicator. The obtained capacity market prices are summarized in Fig. 6.

For the SO capacity target, it can be observed that prices are 0€ /MW as there is no capacity scarcity for the IT1 and IT2 cases. For the IT3 cases, the capacity prices rise above 0 as there is missing capacity in the EOM case. The SB capacity price falls within the RA range, and thus, cannot clearly indicate SB. However, in case the capacity price would exceed the boundary set by the risk-averse case of IT3, it could be used as an indicator for SB if the risk attitude is not known.

For the peak load capacity target, the capacity price is equal to the Costs-Of-New-Entry (CONE) of GEN3 for all market settings for IT1 and IT2, while it exceeds CONE of GEN3 for IT3 clearly indicating that the price bid is strategically motivated.

In summary, we show that RA and SB can be clearly distinguished for base-load capacity, while for mid- and peak-load technology the differentiation may be more challenging. For SO set capacity targets it is not possible to distinguish between RA and SB without knowing the degree of risk-aversion, even when taking capacity market prices into account. For all capacities, we showed that investment decisions of RA and SB agents can be differentiated if the capacity target is set to the peak load. Moreover, we conclude that IT3 agents have a higher potential to drive up prices than other agents, for whom strategic behavior has the highest potential. Lastly, we show that a capacity market cannot mitigate the exercise of market power on the investment level. However, a capacity market with a peak load target alters the investment decisions of RA investors and therefore allows regulators to distinguish risk-averse behavior from strategic behavior.

3.4. Disentangling risk-aversion and strategic behavior using a large set of problem instances

To generalize findings presented in Section 3.2 and 3.3 and to mimic a range of parameter settings, we execute optimizations for a large set of problems. Therefore, we vary investment costs ($C^{I} \in \{100\%, 90\%\}$), marginal costs of production ($C^{OP} \in \{100\%, 110\%\}$) and the demand elasticity ($D^{ela}_{e} \in \{0MW, 500MW\}$) for different capacity targets (0MW, 90% SO, SO, 110% SO, peak) for all technologies. Here, e.g. *110% SO*, refers to 110% of the installed capacity of the social optimal case. The resulting set has 1920 problem instances. For all instances, we indicate the number of outcomes for which RA and SB can be theoretically mixed up (#overlapping). For overlapping instances, we calculate the γ at which RA and SB investments coincide via interpolation for $\beta = 0.1$. The choice of β is motivated by Figs. 2 and 3 showing that a low beta corresponds to lower capacities. Additionally, we state the mean, median, 10%, and 90% quantiles of the outcomes to give information about the γ-distribution.

Results confirm the findings of previous sections. For the EOM setting, for more than 99% of the cases, IT2 and IT3 can lead to mix-ups, while the IT1 case is clearly separable. When capacities of RA and SB coincide, the risk-averse investor of the mid-load technology has a higher risk-aversion than for the peak-load case, implying that a risk-averse peak-load technology investor may be easier confused with a strategic one. While the outcome for the runs with a complementary capacity market with 90% SO target, SO target, and 110% SO target are very similar to the ones of the EOM, having a peak-load target on the capacity market allows distinguishing RA and SB for all considered instances of the problem. This outcome highlights that even if the capacity

Table 3
Mapping strategic behavior into risk-averse behavior using large set of instances and capacity targets set to 0MW (depicting the EOM), to 90%, 100%, 110% of the social optimal (SO) capacity, and to the peak-load.

	CM target														
	0.0 (EOM)			90% SO			SO			110% SO			Peak		
	IT1	IT2	IT3	IT1	IT2	IT3	IT1	IT2	IT3	IT1	IT2	IT3	IT1	IT2	IT3
mean γ	-	0.478	0.818	-	0.477	0.817	-	0.477	0.817	-	0.477	0.817	-	-	-
median γ	-	0.496	0.818	-	0.496	0.813	-	0.496	0.813	-	0.496	0.813	-	-	-
10% quantile γ	-	0.355	0.759	-	0.356	0.773	-	0.356	0.773	-	0.356	0.773	-	-	-
90% quantile γ	-	0.591	0.872	-	0.591	0.869	-	0.591	0.869	-	0.591	0.869	-	-	-
#overlapping	0	126	128	0	127	128	0	127	128	0	127	128	0	0	0
#non-overlapping	126	1	0	128	0	0	128	0	0	128	0	0	128	128	128
#not converged	2	1	0	0	1	0	0	1	0	0	1	0	0	0	0

target is set 10% above the social optimal target, i.e. strategic agents have a potential to abuse their power on the capacity market, distinguishability of these cases are not impacted comparing cases with smaller capacity targets. However, as shown in Table 2, RA agents tend to increase investments for capacity targets set to the peak-load enabling these cases to be distinguished from each other.

3.5. Computational effort

The optimization routines are implemented in Julia and executed on the Vlaams-Supercomputing-Centrum cluster using two Xeon Gold 6140 CPUs@2.3 GHz (Skylake) processors with in total 36 cores and 192GB of RAM. Up to 36 problem instances were solved in parallel. In total, a number of 11127 problems involving risk-averse agents were solved for Table 3. The solution time using ADMM algorithm took in average 305s (median). The 10%- and 90%-quantile were 107s and 2031s, respectively. The problem of a risk-averse investor has 596 variables and 594 constraints. 1920 problem instances for the bi-level problem were solved. Here, the median solution time was 31s, while the 10%- and 90%-quantile were 8s and 312s, respectively. The bi-level problem consists of 2040 variables (1285 continuous, 755 integer) and 2491 constraints.

4. Conclusion

This paper provides a generation expansion problem reflecting strategic and risk-averse behavior to disentangle characteristics of both behaviors based on observed market outcomes.

In a comparative case study, we show that risk-averse and strategic investment behaviors lead to under-investment in capacity from a social planner perspective. Moreover, we show quantitatively that the outcomes of both behaviors can coincide.

For an energy-only market, behaviors can clearly be distinguished if the strategic, or risk-averse, generation company can invest in base-load technology. In contrast, investments in mid- and peak-load technology cannot be distinguished without having additional information about the risk attitude and expectation of the risk-averse investor.

Considering a complementary capacity market, findings are identical for a capacity target set to the social optimal capacity and variations within $\pm$ 10% of the target. However, assuming that the capacity target is set equal to the peak load, the presented study indicates that the capacity market can be exploited to enhance strategic behavior via strategic bids. In this case, risk-averse and strategic behavior can be differentiated.

Implications of this work may be of use for regulators to interpret ex-post market outcomes. The used assumptions of having either risk-averse or strategic agents outline extreme cases. Assuming an investor that is both risk-averse and strategic would increase insights into investors' decision-making. This can be the subject of further research.

CRediT authorship contribution statement

Steffen Kaminski: Conceptualization, Methodology, Software, Writing – original draft, Formal analysis, Visualization. **Mihaly Dolanyi:** Conceptualization, Methodology, Writing – review & editing. **Kenneth Bruninx:** Conceptualization, Methodology, Writing – review & editing. **Erik Delarue:** Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

The research was funded by the Strategic Basic Research (SBO) grant (S006718N) provided by the Research Foundation - Flanders (FWO) and by the University of Leuven's C2 Research Project C24/16/018 entitled "Energy Storage as a Disruptive Technology in the Energy System of the Future". K. Bruninx is a post-doctoral research fellow of the Research Foundation - Flanders (FWO) at the University of Leuven and EnergyVille (mandate no. 12J3320N). The resources and services used in this work were provided by the VSC (Flemish Supercomputer Center), funded by the Research Foundation - Flanders (FWO) and the Flemish Government.

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