Revenue and risk of variable renewable electricity investment: The cannibalization effect under high market penetration

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Revenue and risk of variable renewable electricity investment: The cannibalization effect under high market penetration

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ABSTRACT

Wind and solar power depress market prices at times when they produce the most. This has been termed the 'cannibalization effect', and its magnitude has been established within the economic literature on current and future markets. Although it has a substantial impact on the revenue of VRE technologies, the cannibalization effect is neglected in the capital budgeting literature, including portfolio- and real options theory. In this paper, we present an analytical framework that explicitly models the correlation between VRE production and electricity price, based on the production costs of surrounding generation capacity. We derive closed-form expressions for the expected short-term and long-term revenue, the variance of the revenue and the timing of investments. The effect of including these system characteristics is illustrated with numerical examples, where we find the cannibalization effect to decrease projected profit relative to investment cost from 33% to between 13% and −40%, depending on the assumption for the future VRE capacity expansion rate. Using a real options framework, the investment threshold increases by between 13% and 67%, due to the inclusion of cannibalization.

1. Introduction

With stringent climate targets [1,2] and increasing prices on emission permits [3,4], the European energy sector is in rapid transition. This is especially true for the electricity sector, which offers a large, cost-efficient potential for reducing greenhouse gas emissions [5]. The electricity sector is characterized by long investment horizons; and in the case of carbon-neutral technologies, high investment costs and low running costs. For wind and solar power, the investment costs make up around 75% of the discounted lifetime costs [6]. Due to long payback periods, the financial risk for investors of exposure to low market prices is high.

It has been observed that, with a high market penetration of wind and solar power, prices are depressed during times of high VRE production, leading to value deflation of VRE assets [7–9]. This effect has been termed 'cannibalization' [10], and has been observed both empirically [9,11] and in various models [12–14]. Consequently, uncertainty regarding the future capacity mix, e.g. future VRE capacity growth, significantly affect the appraisal of VRE investment options.

Investment under uncertainty [15] can be addressed from several angles, including portfolio theory [16] and real options analysis [17]. Such methods have also been applied to VRE investments. However, the dynamics of cannibalization have not been recognized in the capital budgeting literature, although the cannibalization effect and the decreasing market value of variable renewables have been classified as major risks for VRE investors [12–14,18]. Baringo and Conejo, for example, identify three major risks faced by an investor in wind power as 'production variability [...], the eventual future decline in wind power investment costs, and the significant financial risk' [19], hence omitting the cannibalization risk.

Other studies of VRE investments consider the uncertainty in investment costs [20,21], fuel prices and demand sensitivity [22] and climate policy [23]. There exists also recent research focusing on regulatory uncertainty regarding support schemes, such as feed-in tariffs [24] other subsidy schemes [25–27] and the withdrawal of subsidies [28]. A few studies include some aspects of price risk in relation to VRE investment. For example, Boomsma et al. [25] use price volatility to assess the risk of a VRE investment and Fleten et al. [29] further account for the correlation between demand and VRE output. Nevertheless, to the best of our knowledge, the future VRE penetration level and its impact on the revenues of VRE assets has not been accounted for in this strand of literature.

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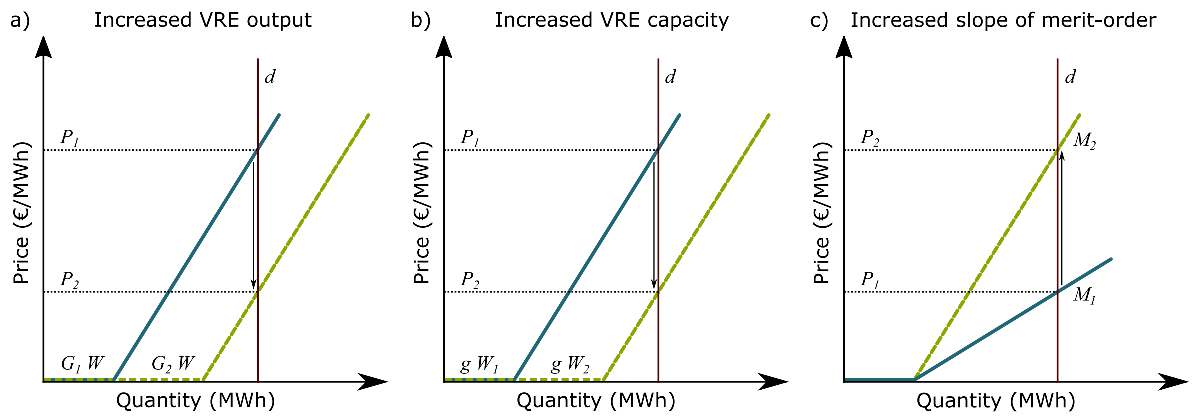

Fig. 1. The effects of changes in the merit-order curve on the electricity price. The fixed demand d is represented by the red line. The blue lines show the initial merit-order curve leading to price P_1, and the green dashed lines the new merit order curve leading to price P_2. In (a), the momentary VRE capacity factor increases from G_1 to G_2. In (b), the VRE generation capacity increases from W_1 to W_2. In (c), the slope of the dispatchable generators' merit order curve increases from M_1 to M_2, e.g. due to an increase in a CO_2 price. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

More specifically, we note that all of the studies cited above [19–25,25–29] model the electricity price as independent of both the future VRE generation capacity and the output profile of VRE generators; either as a stochastic process or using historical prices. The electricity price is modeled as exogenous, thus implicitly assuming no correlation between the price and the generation pattern of a potential investment asset. Thus, by design, the methods of Refs. [20,21,24–28] cannot unveil the risk pertaining to cannibalization.

To capture the cannibalization effect, the methodology has to account for the relationship between VRE generation and market price; either by an endogenously generated price, or by assuming that VRE generation and price are dependent through some other mechanism. We found only one paper where the price is modeled as having a negative dependence on the amount of 'green electricity' capacity in the market, namely Bigerna et al. [30]. However, the paper does not further elaborate on the mechanism, nor how it affects the results. Similar to the situation in the real options literature cited above, a review of portfolio theory for electricity generation investment found no analyses using such endogenous price formation [31].

In contrast to the literature on the cannibalization effect that is either empirical or uses numerical models [7,8,10–14], our approach is analytic and starts with basic economic theory regarding supply, demand, and price. In contrast to the literature on investment decisions under uncertainty for VRE [19–25,25–29], we develop a framework where the price formation is endogenous, thus allowing to investigate the effect of cannibalization on future revenues. The purpose of this paper is to present an analytical model and demonstrate how it can be used as a decision aid in understanding how VRE revenue and risk are influenced by cannibalization.

The contribution of this paper is threefold:

- First, we formalize the cannibalization effect in a short-term market equilibrium with an analytical framework suitable for investment analysis, e.g. for real-options- and portfolio theory. We do this by letting the price (and hence VRE revenues) depend on the fluctuating generation of VRE assets, and by accounting for the correlation between the generation by the investor's VRE asset and the aggregate VRE capacity in the generation mix.
- Second, we use this formalization to derive closed-form expressions for the expected value and variance of the net present value (NPV) of revenues over the VRE plant's lifetime. In this long-term setting, we model the changes in the capacity mix through random walks, separately for VRE and non-VRE assets.
- Third, we illustrate the use of the expression for the expected value by incorporating it into an investment timing ("real options") problem.

2. Method

2.1. Model set-up and assumptions

Consider a wholesale, energy-only electricity market, in which the supply-side includes a mix of VRE and dispatchable generation. We assume that bidding prices are determined by the marginal costs of generation. The electricity price is then determined by the short-term market equilibrium, at the intersection of the merit-order (MO) curve and demand. This set-up is standard short-term equilibrium of supply and demand with VRE, see e.g. [32]. The model sees the electricity price as determined both by the short-term fluctuations of weather-dependent VRE output, as well as by longer-term changes in generation the capacity mix. The latter is represented in the model through changes in the MO curve.

We make the following simplifications in our model:

- Demand remains constant throughout a year and over the lifetime of the plant.
- There is neither electricity storage nor trade with outside markets.
- The MO curve consists of two line segments, which represent VRE and dispatchable generation, respectively (see Fig. 1).
- The market is perfectly competitive, i.e. investors cannot affect the price through strategic bidding. Accordingly, we assume that bidding prices are determined by the marginal costs of generation.

The effects of these simplifications and limitations of the model are discussed later in the paper.

Fig. 1 illustrates the short-term market equilibrium, showing how the price is affected by momentary changes in VRE output (left), longer term changes in VRE capacity (middle) and the steepness of the MO curve segment that represents dispatchable generation (right). The VRE output depends on the installed capacity and the momentary generating conditions (e.g. windiness or solar irradiance). The steepness of the dispatchable generation MO curve depends on the aggregate generating capacity and its mix, and on fuel and emission prices as well as other variable operating costs. As can be seen from the figure, the equilibrium price decreases with an increase in VRE output and capacity level, whereas the price increases with an increase in the costs of dispatchable generation.

Starting from the static description illustrated in Fig. 1, we develop an analytical model that computes the expected value and variance of the net present value (NPV) of future revenues for a unit of VRE capacity. The model encapsulates that the aggregate installed generation capacity mix can change over time due to new investments and decommissioning of old plants, and that the generation costs of dispatchable generation change due to fluctuations in fuel and emission prices.

Table 1
Nomenclature with descriptions and units. For the definition of constants p_1 to p_6, please see Appendix B.

Symbol	Description	Unit
t	time	time unit e.g. [h]
T	lifetime of investor's plant	time unit e.g. [h]
V_t	wind power output time series	[0,1]
S_t	solar power output time series	[0,1]
G_{A_t}	aggregated VRE output	[0,1]
G_{I_t}	investor VRE output	[0,1]
ρ_{G_A,G_I}	Pearson correlation coefficient between G_{A_t}, G_{I_t}	[−1,1]
W_t, w_t	total VRE capacity	[GW]
W_t, w_t	total VRE capacity	[GW]
M_t, m_t	slope of merit order curve	[€/MWh/GW]
d	electricity demand	[GW]
P_t	electricity price	[€/MWh]
R_t	revenue for VRE investor	[€/MW/h]
μ_{G_I}, μ_{G_A}	expected value for G_I and G_A	[0,1]
σ_{G_I}, σ_{G_A}	standard deviation for G_I and G_A	[0,1]
k_1	constant, $d\mu_{G_I}$	[GW]
k_2	constant, $\mu_{G_A}\mu_{G_I}$	[0,1]
k_3	constant, $\rho_{G_AG_I}\sigma_{G_I}\sigma_{G_A}$	[−1,1]
μ_W, μ_M	relative drifts of stochastic variables M_t, W_t	[-∞, ∞]
σ_W, σ_M	relative volatilities of stochastic variables M_t, W_t	[-∞, ∞]
$z_{W,t}$, $z_{M,t}$	Wiener processes for M_t, W_t	time unit e.g. [h]
ρ_{WM}	correlation coefficient between W_t and W_m, $E[dz_{W,t}dz_{M,t}]/dt$	[−1,1]
β	discount rate	[0, ∞]

We model these as stochastic processes that affect the level of VRE capacity and the steepness of the MO curve segment representing the costs of dispatchable generation. Furthermore, we include a stationary stochastic processes that represents the momentary variability in VRE generation.

We derive an expression for the expected revenues in two steps: First, in Section 3, we consider the revenue at a single future point in time. This static approach reflects the instantaneous uncertainty in VRE generation, while treating the MO curve as known. Then, in Section 4, we consider long-term changes in VRE capacity and the MO curve and form closed-form expressions for the expected value and the variance of revenues' net present value (NPV) over the lifetime of the VRE asset. We apply the analytical framework to an investment timing problem in Section 5. All three components of our modeling (instantaneous revenue, life-time revenue and risk, and investment timing) are illustrated with a numerical example, using real-world data for Poland.

To emphasize the impact of incorporating the cannibalization effect, we compare three cases throughout the paper:

- **Case 1**: neither the merit order nor the cannibalization effects are considered. As noted above, most of the existing literature makes this assumption, e.g. by using exogenous prices based on historical data from markets with low shares of VRE.
- **Case 2**: the merit order effect is considered, but the cannibalization effect is not. This is the case for modeling approaches with exogenous price input based on historical data from a market with a high share of VRE.
- **Case 3**: The merit order *and* the cannibalization effects are considered. This is achieved here through endogenous price formation where the momentary VRE generation affects the price, and is the novelty of our framework compared to the previous literature.

2.2. Nomenclature

The symbols used in the analytical model are presented in 1 for easy reference.

2.3. Numerical example and data

The numerical examples (Sections 3.2, 4.3 and 5.2) are based on weather, demand and capacity mix data for Poland. In addition, an estimate regarding the future *change* in VRE capacity and the slope of the merit order curve used in the examples (Sections 4.3 and 5.2) is based on the development in Germany between the years 2005 and 2019. Note, however, that the parameters that represent the rate of change of the capacity composition are fundamentally uncertain and reflect the subjective beliefs of the investor. The values for Germany are thus used merely to find an approximate range for these parameter values. The rationale for using Poland as an illustrative example case is that the country has recently experienced a boom in VRE investment, yet VRE still has a minor share in the overall capacity mix.

Table 2
Statistical properties of the wind, solar and aggregate VRE capacity factors used in the numerical examples throughout the paper. The values for wind and solar are based on the wind/solar share in Poland in 2018, with a VRE capacity mix of 9% solar and 91% wind.

	Mean (μ)	Standard deviation (σ)
Wind, V_t	0.31	0.22
Solar, S_t	0.15	0.22
Aggregate VRE, G_{A_t}	0.30	0.20

The statistical properties for wind, solar, and the aggregate VRE generation of our data set are listed in Table 2. The time series for wind output, $V_t \in [0,1]$, and solar output, $S_t \in [0,1]$, are constructed using ERA 5 weather data from ECMWF and the DTU Global Wind Atlas with the method described in Mattsson et al. [33]. Sites in Poland with a capacity factor of solar above 14% or average wind speed above 6 m/s[1] were aggregated to represent the respective wind and solar output on country level.

To represent the statistical properties of aggregated VRE output G_{A_t}, the wind and solar outputs are weighted using the wind capacity (5.8 GW [34]) and solar capacity (0.6 GW [34]) in Poland in 2018, so that $G_{A_t} = 0.91V_t + 0.09S_t$. The numerical examples assume the potential investment to be in wind power, so the investor's time series is $G_{I_t} = v_t$. For the 91% wind, 9% solar VRE mix, the correlation coefficient between the aggregate VRE mix and the considered wind power asset, ρ_{G_A,G_I}, is 0.995.

The initial VRE capacity w_0 is the sum of wind and solar capacities (5.8 + 0.6 = 6.4 GW in 2018 [34]). The demand d is estimated by

[1] Referring to the partitioning into classes in Ref. [33], this is equivalent to averaging over classes 3–5 for wind and class 2, which is the highest class in Poland, for solar.

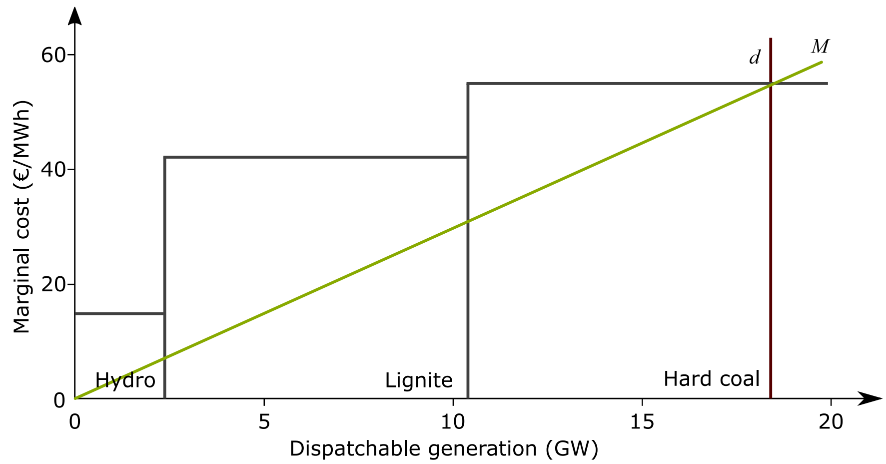

Fig. 2. The linearization of the dispatchable generation merit-order curve for Poland in 2018. The linearization is done between the origin and the level of average demand d, yielding the merit-order slope M.

dividing the annual demand in Poland in 2018 by the number of hours, equaling 18.5 GW.

The initial slope m_0 of the MO curve representing dispatchable generation is based on a bottom-up estimate of the generation mix in Poland. The capacities of hydro power are from [34] and all other capacities from [35]. The variable cost pertaining to each dispatchable technology is found by adding fuel-, variable O&M- and CO_2 cost, see Appendix A for details and data sources.

We finally determine the slope m_0 by linearizing the resulting dispatchable MO curve between the origin and dispatchable generation at level d (18.5 GW), where hard coal is at the margin with the variable cost of 55 €/MWh (see Fig. 2). The slope is found to be $m_0 = 3.0 \cdot 10^{-3}$ $\frac{\text{€/MWh}}{\text{GW}}$.

The long-term evolution of VRE and dispatchable generation capacity in Sections 4.3 and 5.2 is represented by random walks using Geometric Brownian Motions. The growth and volatility of these random walks reflect the investor's subjective views about an uncertain future, and definite values cannot therefore be assigned. Instead, we illustrate our results with a range of these parameters. We draw an analogy from the past: the rapid expansion of VRE capacity in Germany; with an underlying idea that Poland might be in the early stage of similar progress. The share of VRE generation of total electricity demand in Poland 2018, approximately 10% of the annual electricity generation, is equal to that of Germany in 2005.

The average, annual growth in VRE capacity is found to be 13% in Germany between the years 2005 and 2019, with a standard deviation of 6%. However, there was a significant, declining drift in the VRE expansion rate, with years around 2010 experiencing over 20% growth, whereas years towards 2019 had growth well below 10%. The dispatchable MO curve slope grows annually on average by 1.1%, having a standard deviation of 4.8%. The correlation between these is -14%. As any assumptions about future development are inherently speculative, we carry out an extensive sensitivity analysis for each parameter in the following sections and the Appendix.

3. Instantaneous revenue

We start by considering the market equilibrium, price and revenue at a single future point in time t. The treatment is standard short-term equilibrium, where price is determined at the intersection of demand and supply curves (see e.g. [32]).

3.1. Derivation

To determine the equilibrium price P_t, let electricity demand be d. Let w_t be the *aggregate* VRE capacity in the market, with the instantaneous capacity factor represented by a random variable $G_{A,t} \in [0,1]$.[2] Then, $w_t G_{A,t}$ is the electricity generated by VRE. If $w_t G_{A,t} \leq d$, the dispatch of the non-VRE plants is $d - w_t G_{A,t}$. Assuming that the variable generation costs of VRE are zero and the dispatchable MO curve is linear with slope $m_t > 0$, the short-term equilibrium price P_t is described by the function $P_t = \max\{m_t(d - w_t G_{A,t}), 0\}$, as was illustrated in Fig. 1. For simplicity, however, we assume the MO curve is the function:

$$P_t = m_t(d - w_t G_{A,t}), \tag{1}$$

which allows negative prices if $d < w_t G_{A,t}$. This function is linear in the non-VRE power dispatch and affine in VRE output. As a result, P_t is a random variable and $G_{A,t}$ and P_t are perfectly correlated.

Now, consider the *investor's* VRE plant. Let $G_{I,t} \in [0,1]$ be a random variable that represents the capacity factor of this plant at time t, with expected value μ_{G_I} and variance $\sigma^2_{G_I}$. Similarly for the capacity factor of *aggregate* VRE in the region, $G_{A,t}$, let the expected value be μ_{G_A} and variance $\sigma^2_{G_A}$. For simplicity, we assume that neither the means nor the variances of $G_{I,t}, G_{A,t}$ vary over time. Note that $G_{I,t}$ and P_t may not be perfectly correlated, but are indeed (negatively) correlated if $G_{I,t}$ and $G_{A,t}$ are (positively) correlated. As an example, if the aggregated VRE generation in the market is dominated by wind, and if the investor is also considering a wind power investment, then $G_{A,t}$ and $G_{I,t}$ will be highly correlated. However, if the investor considers a solar power investment $G_{A,t}$ and $G_{I,t}$ would be less correlated. Last, assume that the investor's plant is small enough not to affect the equilibrium price significantly.

The revenue per unit capacity of the investor's VRE plant at time t is $R_t = P_t G_{I,t}$. The expected value of the random variable R_t is

$$\begin{aligned} E[R_t] &= E[P_t G_{I,t}] = E[m_t(d - G_{A,t} w_t) G_{I,t}] \\ &= m_t(d\,E[G_{I,t}] - w_t E[G_{I,t} G_{A,t}]) \\ &= m_t(d\,E[G_{I,t}] - w_t(Cov(G_{I,t}, G_{A,t}) + E[G_{I,t}]E[G_{A,t}])) \\ &= m_t d \mu_{G_I} - m_t w_t \mu_{G_I} \mu_{G_A} - m_t w_t \rho_{G_I,G_A} \sigma_{G_I} \sigma_{G_A} \end{aligned} \tag{2}$$

where ρ_{G_I,G_A} is the correlation coefficient between $G_{I,t}$ and $G_{A,t}$.

Eq. (2) shows that, with an linear merit order curve, the expected revenue for a VRE owner is a linear function (or more precisely, affine)

[2] In our notation, capital letters denote random variables and lowercase letters denote deterministic parameters.

of the system's VRE capacity w_t. Moreover, for $\rho_{G_I,G_A} > 0$, the expected revenue $E[R_t]$ decreases with w_t. The rate of decrease depends on the mean (μ_{G_A}) and variance (σ_{G_A}) of the aggregated VRE output, the mean (μ_{G_I}) and variance (σ_{G_I}) of the investor's output, as well as the correlation ρ_{G_I,G_A} between these two.

In Eq. (2), the parameters w_t and m_t are subject to change in the long-term, whereas the remaining parameters do not change over time.[3] We can thus simplify Eq. (2) to:

$$E[R_t] = k_1 m_t - (k_2 + k_3) m_t w_t \tag{3}$$

where $k_1 = d\mu_{G_I}$, $k_2 = \mu_{G_A}\mu_{G_I}$ and $k_3 = \rho_{G_I,G_A}\sigma_{G_I}\sigma_{G_A}$.

To understand the significance of Eqs. (2) and (3) better in relation to the merit order and cannibalization effects, we can separate it into three terms:

- The first term, $k_1 m_t$, corresponds to the revenue for a VRE plant if there is no VRE in the system or if the decrease in revenue due to the merit-order and cannibalization effects is ignored. Considering only this term, with $k_2 = k_3 = 0$, corresponds to our **Case 1**.
- The second term, $-k_2 m_t w_t$, stems from *the merit order effect*. This effect increases as the energy contribution from VRE, w_t, increases. Considering this term in addition to the first part, i.e. $k_2 > 0, k_3 = 0$, corresponds to our **Case 2**.[4]
- The third term, $-k_3 m_t w_t$, represents *the cannibalization effect*. This term takes into account the correlation, ρ_{G_I,G_A}, between the aggregated VRE generation ($G_{A,t}$) and the generation of the investor's plant ($G_{I,t}$). If the revenue is assessed as the sum of all three terms, then the revenue is determined by the amount of VRE in the system (MO effect), as well as the timing of investors' generation compared to the aggregate VRE generation (cannibalization). Including the second and third terms ($k_2 > 0, k_3 > 0$) in the revenue assessment corresponds to our **Case 3**.

Note that the revenue decreases linearly with k_2 and k_3. Thus, both the merit order- and cannibalization effects reduce expected revenue.

3.2. Numerical example

We use the values from Section 2.3 for a prospective wind power investment in Poland. These values generate parameters $k_1 = 5.75$ GW, $k_2 = 0.092$ and $k_3 = 0.044$. Furthermore, in this example, we assume that the VRE capacity, which in 2018 was about one third of the average demand, has increased so that it is equal to the demand, $w_t = d$. The slope of the merit order curve is $m_t = 0.003$ €.[5]

Given these numbers, the average revenues are presented in Table 3. The table shows the average hourly revenue per unit investment (in €/MW/h) for the three cases, as well as the average return per unit of electricity generated (in €/MWh), using the average capacity factor $\mu_{G_I} = 0.31$. The average return per unit of electricity may be compared against the LCOE (Levelized Cost of Electricity) of wind power, which in this case is 38 €/MWh, using the cost data of Table A.8 in Appendix A.

[3] These can be estimated from data on wind or solar time series. If the relative shares of wind and solar change over time, the values pertaining to the aggregated VRE output, $\mu_{G_A}, \sigma_{G_A}, \rho_{G_A,G_I}$ will change with time, but here we assume a fixed ratio between wind and solar, which entails that wind and solar have the same growth rate.

[4] To assume $k_3 = 0$ is justified if price and generation is uncorrelated, i.e., $\rho_{G_I,G_A} = 0$. In reality, this may happen e.g. if the generator is geothermal electricity, which has a flat output profile. It may also be the case that the correlation is negative, $\rho_{G_I,G_A} < 0$, which may happen e.g. if the investor's generator is solar PV in a system dominated by wind power, since solar PV has seasonal pattern opposite that of wind.

[5] Computed assuming coal on the margin, with variable cost, including the EU-ETS price, of 55 €/MWh.

Table 3
Average, instantaneous revenue estimates in the three cases, calculated as per-MW-per-hour and per generated electricity.

	Revenue (per MW, per hour)	Revenue (per generated MWh)
Case 1	17 €	55 €
Case 2	12 €	39 €
Case 3	10 €	31 €

Thus, for an investor who does not consider the MO- and cannibalization effects and hence makes her investment assessment according to **Case 1**, it looks as though she will make an average profit of 55–38 = 17 € for each MWh generated (equivalent to a 45% profit margin). However, if the MO- and cannibalization effects are considered (**Case 3**), the investment calculation yields a loss of 38–31 = 7 € for every MWh generated (equivalent to a negative profit of 18%).

4. Long-term expected revenue and risk

In computing the short-term revenue, the level of VRE capacity in the system and the slope of the merit-order curve, w_t and m_t, were known constants. However, these two parameters change over the lifetime of a potential investment: the VRE capacity will change as other investors decide to install new or retire existing capacity; while the slope of the merit order curve may change due to investments and decommissioning of dispatchable power plants, or due to changes in fuel and CO_2 prices. All of these involve notable uncertainties. In the long term, the values m_t and w_t may be seen as particular realizations of the random variables M_t and W_t.

4.1. Derivation of the expected net-present-value of the revenue

We represent the long-term uncertainties regarding VRE capacity, W_t, and MO slope, M_t, by Geometric Brownian Motion (GBM). GBM has been frequently used in the literature to present the volatility in electricity prices [25,29] or the level of demand [36]. However, as we calculate the price endogenously through the short-term market equilibrium, representing the price through GBM is not possible. Instead, we use GMB to represent changes in the generation capacity in a manner analogous to [37]. Market-level models with capacity expansion can model equilibrium investments [5], often assuming perfect foresight to the future. However, our model scope does not include the long-term market equilibrium, only the beliefs of the considered investor. These beliefs could as well represent one's subjective and imperfect foresight [38], or rational expectations that match a long-term market equilibrium [39].

Let $\{W_t\}$ and $\{M_t\}$ be the two stochastic processes that follow the stochastic differential equations [40]:

$$dW_t = \mu_W W dt + \sigma_W W dz_{W,t}, \tag{4}$$

$$dM_t = \mu_M M dt + \sigma_M M dz_{M,t}, \tag{5}$$

where μ_W and μ_M are relative drifts, σ_W and σ_M are relative volatilities, and $\{z_{W,t}\}$ and $\{z_{M,t}\}$ are Wiener processes with $E[dz_{W,t}dz_{M,t}] = \rho_{WM}dt$.

As a consequence, the level of VRE capacity w_t and the slope of the merit-order curve m_t are strictly positive. The Geometric Brownian motion gives rise to a lognormal distribution with parameters that change with time.[6] We denote the initial state at $t = 0$ with $W_0 = w_0$ and $M_0 = m_0$.

[6] Note that the log-normal distribution means that there is a non-zero probability of values of W_t that are much higher than demand and, as a consequence of our MO curve (Eq. (1)), produce negative prices. The validity of the model is constrained to parameterizations for which this probability remains negligible.

Let $\{G_{A,t}\}$ and $\{G_{I,t}\}$ be stationary stochastic processes of capacity factors, i.e. means and variances are constant over time, as above. We assume that $G_{A,t}, G_{A,s}, G_{I,t}$ and $G_{I,s}$ are mutually independent for $t \neq s$. We also assume that both G_t and $G_{A,t}$ are independent of W_t and M_t. However, W_t and M_t are not necessarily independent of each other, since it is quite possible that, as the capacity of VRE (W_t) increases, part of the dispatchable capacity may be retired, thus potentially increasing the MO slope (M_t). Future revenues are discounted with a rate of β.

By using the expression in Eq. (3) for the instantaneous expected revenues, we can derive the expected net present value (NPV) of revenues over the lifetime T of a unit of VRE capacity. For known values of the VRE capacity level and slope of the MO curve at time 0, $W_0 = w_0$ and $M_0 = m_0$, the NPV of future revenue is:

$$
\begin{aligned}
V(w_0, m_0) &= E^{w_0,m_0}_{G,W,M}\left[\int_0^T e^{-\beta t} R(G_t, W_t, M_t) dt\right] \qquad (6)\\
&= \int_0^T e^{-\beta t} E^{w_0,m_0}_{G,W,M}\left[R(G_t, W_t, M_t)\right] dt\\
&= \int_0^T e^{-\beta t} E^{w_0,m_0}_{W,M}\left[E^{w_t,m_t}_{G_t|W,M}\left[R(G_t, w_t, m_t)\right]\right] dt\\
&= \int_0^T e^{-\beta t} E^{w_0,m_0}_{W,M}\left[E_{G_t}\left[R(G_t, W_t, M_t)\right]\right] dt\\
&= \int_0^T e^{-\beta t} \left(k_1 E^{m_0}_{M}\left[M_t\right] - (k_2 + k_3) E^{w_0,m_0}_{W,M}\left[W_t M_t\right]\right) dt\\
&= \int_0^T e^{-\beta t} \left(k_1 m_0 e^{\mu_M t} - (k_2 + k_3) w_0 m_0 e^{\mu_{WM} t}\right) dt\\
&= m_0\left(k_1 \frac{1 - e^{-(\beta-\mu_M)T}}{\beta - \mu_M} - w_0(k_2 + k_3)\frac{1 - e^{-(\beta-\mu_{WM})T}}{\beta - \mu_{WM}}\right)
\end{aligned}
$$

where for $\{W_t\}$ and $\{M_t\}$ we use the notation $S = \{S_t\}$ and $E^{s_0}_S[g(S_t)] = E_S[g(S_t) \mid S_0 = s_0]$. The second equality is follows from Fubini's theorem, the third equality uses the law of total expectations and the independence of short-term uncertainties (G_t and G_s are independent for $t \neq s$), the fourth exploits the independence of short-term and long-term uncertainties (G_t and W_s as well as G_t and M_s are independent for all t, s) and the fifth that $\{M_t W_t\}$ is a GBM with drift $\mu_{WM} = \mu_M + \mu_W + \rho_{WM}\sigma_W\sigma_M$. Moreover, with S following a GBM with drift μ, the expected value of S_t is $E^{s_0}_S[S_t] = s_0 e^{\mu t}$.

Expression (6) is structurally similar to Eq. (2), and shows that the expected NPV of revenue decreases linearly with k_2 and k_3. Thus, both the merit order- and cannibalization effects reduce expected revenue, in accordance with the intuition and empirical knowledge about these effects.

Furthermore, if $k_2 = k_3 = 0$ (**Case 1**), the expected net present value of the VRE plant increases with the drift of the slope of the merit order line μ_M; but the expected revenue is unaffected by the evolution of VRE capacity $\{W_t\}$, as the merit order and/or cannibalization effects are disregarded. If, on the other hand, $k_2 + k_3 > 0$ (**Cases 2 and 3**), the merit order and/or cannibalization effects are present, which reduces the impact of μ_M on expected revenue. Overall, μ_M affects the expected revenues in an exactly opposite way than the discount rate β.

The cannibalization effect is strengthened particularly by the drift of the VRE capacity, μ_W, i.e. a faster growth rate in the total VRE capacity in the system depresses the revenues more. A smaller impact comes from ρ_{WM}, and also from σ_W and σ_W if $\rho_{WM} > 0$. For numerical investigations of expected revenues as a function of different drift coefficients μ_W and μ_M, and the impacts of the merit order and cannibalization effects (setting $k_2 + k_3 > 0$), see Section 4.3.

4.2. Derivation of the variance of the revenue

An investor is typically interested not only in the expected revenue, but also in the risk. Here, we measure risk through the variance of discounted revenues, and develop an analytical expression for this. The variance is given by

$$
\begin{aligned}
Var(w_0, m_0) = &\, E^{w_0,m_0}_{G,W,M}\left[\left(\int_0^T e^{-\beta t} R(G_t, W_t, M_t) dt\right)^2\right]\\
&- E^{w_0,m_0}_{G,W,M}\left[\int_0^T e^{-\beta t} R(G_t, W_t, M_t) dt\right]^2 \qquad (7)
\end{aligned}
$$

A closed-form expression for the variance is derived in Appendix B, arriving at:

$$
\begin{aligned}
Var(w_0, m_0) = &\, 2m_0^2 \Bigg(k_1^2 \frac{p_2 + p_1 e^{(p_1+p_2)T} - (p_1 + p_2) e^{p_1 T}}{p_1 p_2 (p_1 + p_2)} \qquad (8)\\
&- w_0 k_1 (k_2 + k_3) \frac{p_4 + p_1 e^{(p_1+p_4)T} - (p_1 + p_4) e^{p_1 T}}{p_1 p_4 (p_1 + p_4)}\\
&- w_0 k_1 (k_2 + k_3) \frac{p_5 + p_3 e^{(p_3+p_5)T} - (p_3 + p_5) e^{p_3 T}}{p_3 p_5 (p_3 + p_5)}\\
&+ w_0^2 (k_2 + k_3)^2 \frac{p_6 + p_3 e^{(p_3+p_6)T} - (p_3 + p_6) e^{p_3 T}}{p_3 p_6 (p_3 + p_6)} \Bigg)\\
&- m_0^2 \left(k_1 \frac{1 - e^{-p_1 T}}{p_1} - w_0 (k_2 + k_3) \frac{1 - e^{-p_3 T}}{p_3}\right)^2 .
\end{aligned}
$$

This expression uses the following shorthands for the parameters of the GBSs and β:

$$
\begin{aligned}
p_1 &= \mu_M - \beta \qquad (9)\\
p_2 &= \mu_M - \sigma_M^2 - \beta\\
p_3 &= \mu_{WM} - \beta\\
p_4 &= \mu_{WM} + \rho_{WM}\sigma_W\sigma_M + \sigma_M^2 - \beta\\
p_5 &= \mu_M + \rho_{WM}\sigma_W\sigma_M + \sigma_M^2 - \beta\\
p_6 &= \mu_{WM} + \sigma_{WM}^2 - \beta.
\end{aligned}
$$

This expression is significantly more complicated than Eqs. (3) and (6) for the short-term and long-term expected revenue; and thereby the expression does not allow clear interpretation for how the different parameters affect the revenue variance. In order to obtain further insights regarding the dependence of the variance on merit-order and cannibalization effects, as well as on the parameters of the GBMs, we carry out numerical investigations in the next section.

4.3. Numerical example

We assess the expected revenue and risk by implementing Eq. (6) and (8) with parameter values for Poland, as described in Section 2.3. In addition to the parameter values pertaining to demand, wind- and solar output, which yield the constants $k_1 = 5.75$ GW, $k_2 = 9.2 \cdot 10^{-2}$, $k_3 = 4.4 \cdot 10^{-2}$ (see Section 2.3), we assume the starting values for the Polish system in 2018 to be $M_0 = 3 \cdot 10^{-3}$ and $W_0 = 6.4$ GW, again in accordance with the assessment in Section 2.3. We set the discount rate, β, to 5%.

We estimate plausible values for the (future) relative drifts (μ_W and μ_M) and relative volatilities (σ_W and σ_M) of the VRE capacity and the merit-order slope on the basis of the German electricity system between the years 2005 and 2019, as presented in Section 2.3. An exception is the average VRE growth rate μ_W. Germany experienced an unprecedented VRE capacity expansion during this period, on average 13% per year; fueled partly by strong subsidy schemes, and which has lead e.g. to more frequent negative prices [see e.g.41]. Negative prices can also become a problem in terms of the validity of our model, and the effect of such starts to become significant around 10% average annual VRE growth rate (see Appendix F). Therefore, in this example we use a more conservative assumption of 5% average VRE capacity expansion as the default case and 10% as the high-end of the range. We calculate the expected revenues and their standard deviation by varying one of the random walk parameters ($\mu_W, \mu_M, \sigma_W, \sigma_M$) at a time, while

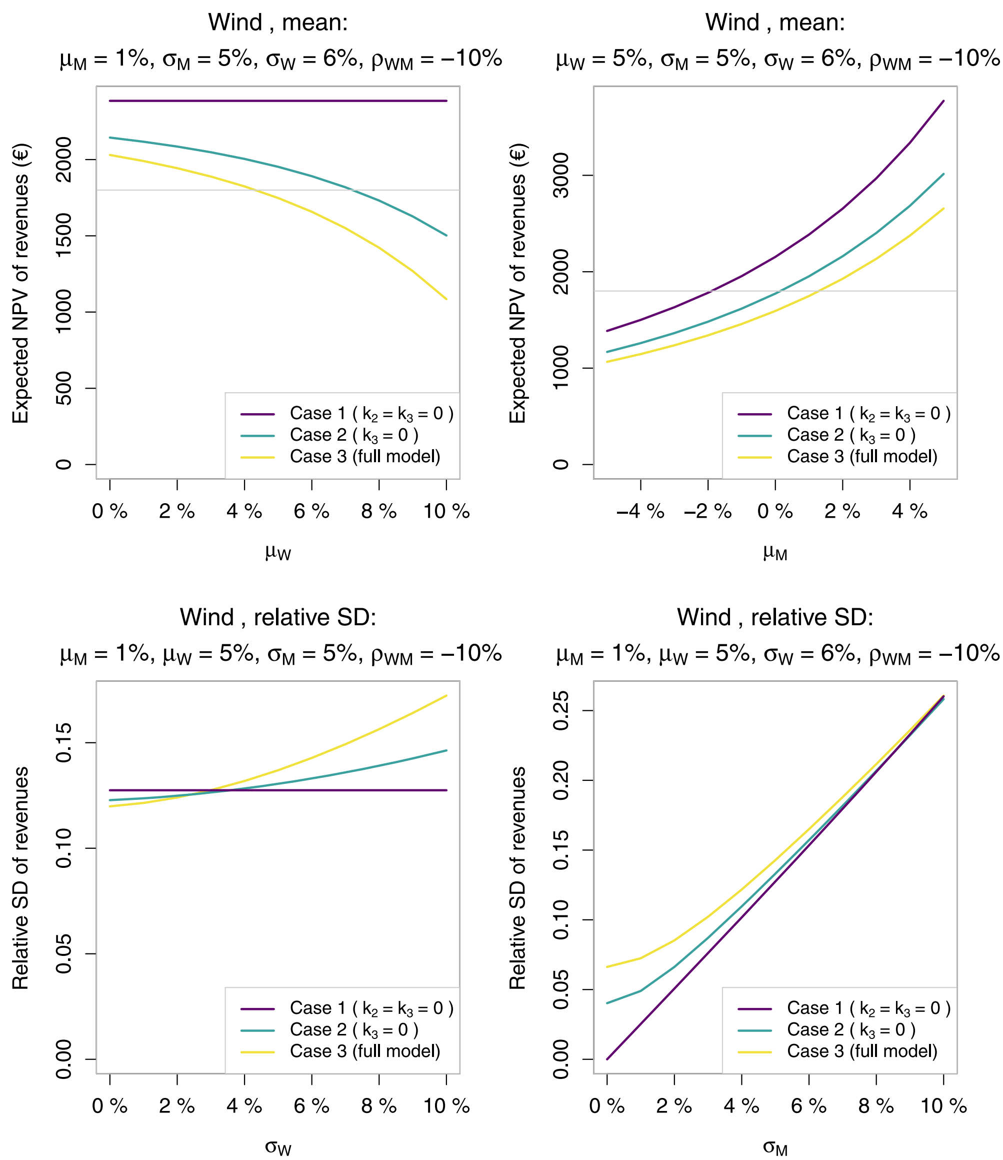

Fig. 3. Expected NPV (top, in euros) and standard deviation relative to the expected value (bottom) for 1 kW wind power investment. Expected NPVs are presented for different expected values, μ_M and μ_W, and standard deviations, σ_M and σ_W, along the x-axes. The other parameter values are given on top of each figure. Different colors indicate the full model (yellow), omitting cannibalization (teal), and omitting VRE merit-order effect and cannibalization (purple). The gray horizontal lines on the top panels indicate the NPV of investment and operating costs. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 4
The parameter ranges and default values for the Geometric Brownian Motions for $\{W_t\}$ and $\{M_t\}$.

	Default	Range min	Range max
VRE growth μ_W	5%	0%	10%
VRE volatility σ_W	6%	0%	10%
MO slope growth μ_M	1%	−5%	5%
MO slope volatility σ_M	5%	0%	10%
VRE and MO correlation ρ_{WM}	−10%	–	–

keeping the others at their default values. The parameter ranges and the default values are presented in Table 4.

The expected revenues and risks for a wind power investment are presented in Fig. 3. The results can be analyzed from two perspectives: (1) the effect of considering or omitting the merit-order and cannibalization effects on future revenue estimates by comparing **Cases 1**, **2** and **3**; and (2) the effect of subjective estimates about the future evolution of $\{W_t\}$ and $\{M_t\}$ on expected returns and risk, by analyzing **Case 3** for different values of the growth and volatility parameters.

The top figures shows that the merit-order and cannibalization effects clearly affect the expected revenues, and these are especially amplified by a stronger VRE capacity growth rate (top left). This is intuitive, since a higher share of VRE in the generation mix leads to stronger cannibalization. The impact of the merit order- and cannibalization effects on revenue risk is far less pronounced (the figures in the bottom), although the effect depends somewhat on the volatility parameters. Please see Fig. E.5 in the Appendix for further results regarding other parameters.

How largely merit-order and cannibalization effects affect investment profitability is noteworthy (c.f. the large difference between the lines representing the three cases in Fig. 3). To provide a point of comparison for the expected life-time revenue, the top figures include an estimate of the NPV of investment- and O&M costs (the gray line at 1800 €/kW). We note that omitting the merit-order and cannibalization effects (**Case 1**) yields a profit which is independent of μ_W (top left). In addition, for **Case 1**, break-even is estimated to be reached even with a flattening MO curve (see $\mu_M < 0$, top right). This means that any model that omits the cannibalization effect is prone to overestimate expected revenues. Such a model would deem an investment profitable under a relatively large range of subjective parameter values regarding the future, although the investment could be unprofitable by expectation in reality.

When focusing on the full model, i.e. **Case 3**, it is evident that a strong future expansion of VRE capacity (μ_W, top left) will eat the profits from a current investment, while the volatility (σ_W, bottom left) has a significant effect on the risks, especially in the case of high volatility of VRE capacity. Yet, the changes related to the slope of the MO curve (μ_M and σ_M, top and bottom right) have even more impact on expected revenues and risk within the assessed parameter range. This is intuitive, as the MO curve is the primary determinant for price formation. Any changes in the MO curve will directly translate into prices and revenues.

Further illustration of expected revenues and risk with respect to all random walk parameters is provided in Fig. E.5. This figure highlights that also the other parameters not presented in Fig. 3 do affect expected revenues and risk considerably, but omitting the merit-order and cannibalization effects does not make substantial difference with regard to some parameters (e.g. the effect of μ_M on risk).

5. Investment timing

Since the VRE capacity level and the MO curve develop over time, investment may be postponed until such market conditions are sufficiently favorable. For this reason, we address the problem of investment timing and how it is influenced by the price impact and the cannibalization effect. We follow the lines of [17] for uncertainty in the MO slope only and [42,43] for uncertainty in both the MO slope and VRE capacity.

5.1. Derivation

The investment timing problem relies on the expected net present value derived in the previous sections. At time t, the expected net present value of revenues over the lifetime of the plant is:

$$V(W_t, M_t) = M_t(a - W b_t),$$

with constants

$$a = k_1 \frac{1 - e^{-(\beta-\mu_M)T}}{\beta - \mu_M}, \quad b = (k_2 + k_3)\frac{1 - e^{-(\beta-\mu_{WM})T}}{\beta - \mu_{WM}}.$$

Thus, we express the expected value as a function of the VRE capacity level and slope of the MO curve which both develop stochastically over time. For known values of the capacity and the slope at time t, $W_t = w_t$ and $M_t = m_t$, $V(W_t, M_t)$ is known. However, at time 0, $V(W_t, M_t)$ is random for $t > 0$.

We consider an infinite option to defer investment until the VRE penetration and an accompanying development of the MO curve justifies it. Clearly, this is a bivariate real options problem. For known values of the capacity and the slope at time 0, $W_0 = w_0$ and $M_0 = m_0$, the investment timing problem is

$$F(w_0, m_0) = \max_{\tau}\{E^{w_0,m_0}_{W,M}[e^{-\beta\tau}(V(W_\tau, M_\tau) - I)]\}, \tag{10}$$

i.e., the problem is to determine the time τ at which the expected net present value is maximized (provided such τ exists). I denotes the investment costs. The solution to the investment timing problem is derived in Appendix C.

Consider first the case of $k_2 + k_3 > 0$, and thus $b > 0$, covering **Cases 2** and **3**. We assume the existence of interdependent thresholds (W^*, M^*) for the VRE capacity and the MO slope such that investment is optimal under sufficiently favorable conditions, i.e. when $(W_t, M_t) = (W^*, M^*)$, where $W^*, M^*, \alpha_W, \alpha_M$ solve

$$\frac{1}{2}\Big(2\rho_{WM}\sigma_W\sigma_M\alpha_W\alpha_M + \sigma_W^2\alpha_W(\alpha_W - 1) + \sigma_M^2\alpha_M(\alpha_M - 1)\Big) + \mu_W\alpha_W + \mu_M\alpha_M - \beta = 0 \tag{11}$$

and

$$W^* = -\frac{a}{b}\cdot\frac{\alpha_W}{\alpha_M - \alpha_W}, \quad M^* = \frac{I}{a}\cdot\frac{\alpha_M - \alpha_W}{\alpha_M - 1}. \tag{12}$$

This defines the decision of investment timing: For fixed W_t, investment is optimal for a sufficiently high MO slope, $M_t \geq M^*(W_t)$, or for fixed M_t, investment is optimal for a sufficiently low VRE capacity $W_t \leq W^*(M_t)$.

Here, we express the threshold for the MO slope as a function of the VRE capacity. The expression of the threshold for VRE capacity as a function of MO slope can be found in Appendix C. For an observed level of VRE capacity, i.e. fixed W, α_M solves

$$\frac{1}{2}\Big(-2\rho_{WM}\sigma_W\sigma_M\Big(\frac{Wb}{a-Wb}\Big) + \sigma_W^2\Big(\frac{Wb}{a-Wb}\Big)^2 + \sigma_M^2\Big)\alpha_M(\alpha_M - 1) + \Big(\frac{1}{2}\Big(-2\rho_{WM}\sigma_W\sigma_M\Big(\frac{Wb}{a-Wb}\Big) + \sigma_W^2\Big(\frac{Wb}{a-Wb}\Big)\Big(\frac{a}{a-Wb}\Big)\Big) - \mu_W\Big(\frac{Wb}{a-Wb}\Big) + \mu_M\Big)\alpha_M - \beta = 0 \tag{13}$$

and

$$M^*(W) = \frac{I}{a - Wb}\cdot\frac{\alpha_M}{\alpha_M - 1}. \tag{14}$$

The analytical solution facilitates comparative statics. Note that $d\alpha_M/d\mu_M < 0, d\alpha_M/d\mu_W > 0, d\alpha_M/d\sigma_M < 0$ and $d\alpha_M/d\sigma_W < 0$ for $a - Wb > 0$ and $\rho_{WM} < 0$, see Appendix D. Now,

$$\begin{aligned}\frac{dM^*}{d\mu_M} &= -\frac{I}{(a-Wb)^2}\cdot\frac{\alpha_M}{\alpha_M - 1}\cdot\Big(\frac{k_1}{k_2+k_3} - W\Big)\cdot\frac{db}{d\mu_{WM}} \\ &\quad - \frac{I}{a-Wb}\cdot\frac{1}{(\alpha_M-1)^2}\cdot\frac{d\alpha_M}{d\mu_M}, \\ \frac{dM^*}{d\mu_W} &= \frac{I}{(a-Wb)^2}\cdot\frac{\alpha_M}{\alpha_M - 1}\cdot W\cdot\frac{db}{d\mu_{WM}} \\ &\quad - \frac{I}{a-Wb}\cdot\frac{1}{(\alpha_M-1)^2}\cdot\frac{d\alpha_M}{d\mu_W},\end{aligned}$$

where $I > 0, \alpha_M > 1$ and $db/d\rho_{WM} > 0$ such that the first term of $dM^*/d\mu_M$ is negative for $k_1 - (k_2 + k_3)W > 0$ and the first term of $dM^*/d\mu_W$ is positive. Since the second term of $dM^*/d\mu_M$ is positive for $a - Wb > 0$, M^* can be increasing for some μ_M and non-increasing for others. Also, since the second term of $dM^*/d\mu_W$ is negative for $a - Wb > 0$, M^* can likewise be increasing for some μ_W and non-increasing for others. Thus, with merit order and/or cannibalization effects, a higher drift of the MO slope or the VRE capacity may slow down or accelerate investment, depending on the current drift. Also,

$$\begin{aligned}\frac{dM^*}{d\sigma_M} &= \frac{I}{(a-Wb)^2}\cdot\frac{\alpha_M}{\alpha_M - 1}\cdot\rho_{WM}\sigma_W W\cdot\frac{db}{d\mu_{WM}} \\ &\quad - \frac{I}{a-Wb}\cdot\frac{1}{(\alpha_M-1)^2}\cdot\frac{d\alpha_M}{d\sigma_M}, \\ \frac{dM^*}{d\sigma_W} &= \frac{I}{(a-Wb)^2}\cdot\frac{\alpha_M}{\alpha_M - 1}\cdot\rho_{WM}\sigma_M W\cdot\frac{db}{d\mu_{WM}} \\ &\quad - \frac{I}{a-Wb}\cdot\frac{1}{(\alpha_M-1)^2}\cdot\frac{d\alpha_M}{d\sigma_W},\end{aligned}$$

where $db/d\mu_{WM} < 0$ such that the first terms are positive for $\rho_{WM} < 0$. Since the second term of $dM^*/d\sigma_M$ is likewise positive for $a - Wb > 0$, M^* is increasing with σ_M. The same applies for M^* as a function of σ_W. As a result, a higher volatility of the MO slope or the VRE capacity always defer investment. We confirm the comparative statics in our numerical investigations, see Section 5.2.

In Appendix D, we further investigate the comparative static of M^* with respect to b. We show that the merit order and/or cannibalization effects may slow down or accelerate investment, depending on the

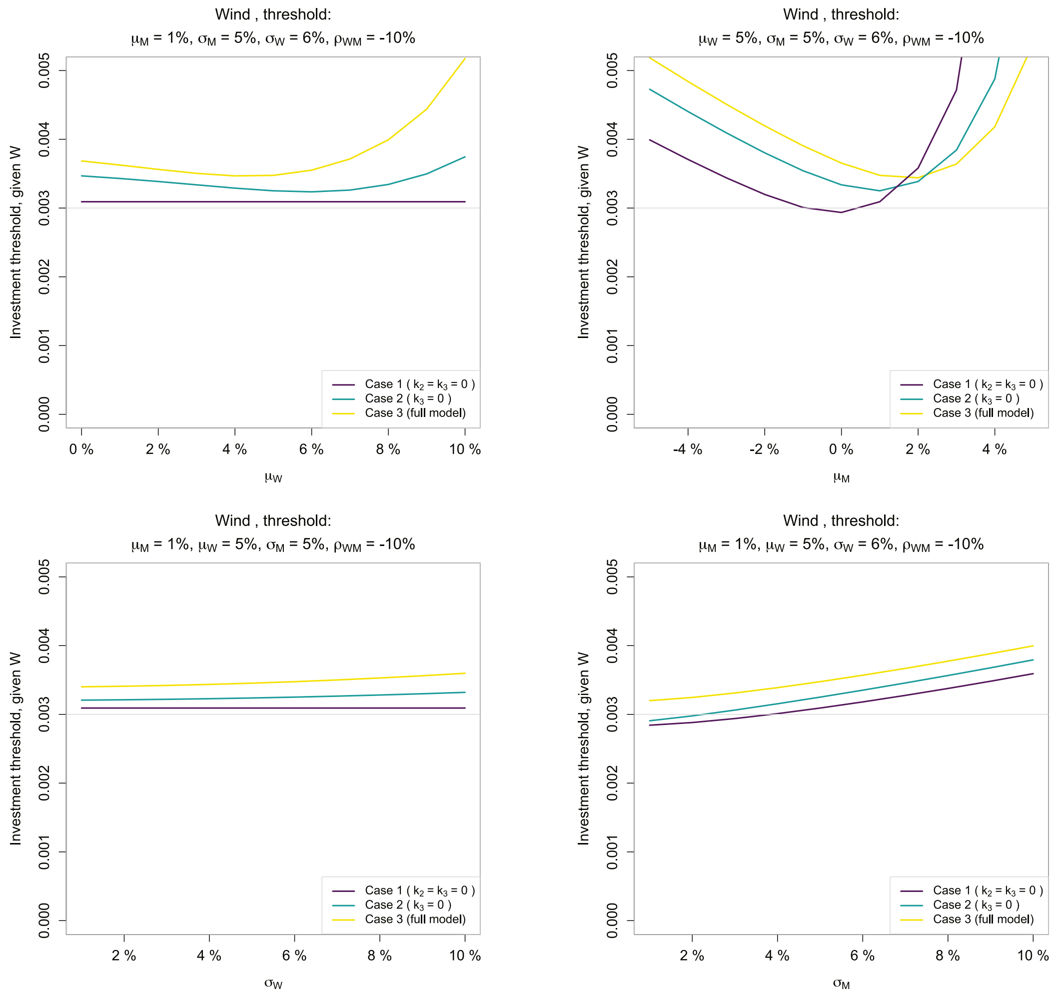

Fig. 4. Investment thresholds (in euros) for the slope of the MO curve, M^*, given VRE capacity level, W, for 1 MW wind power investment. Thresholds are presented for different expected values (top), μ_M and μ_W, and standard deviations (bottom), σ_M and σ_W, along the x-axes. Other parameter values are given on top of each figure. Different colors indicate the full model (yellow), omitting cannibalization (teal), and omitting VRE merit-order effect and cannibalization (purple). The gray horizontal lines indicate the initial slope of the MO curve, m_0. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

drifts and volatilities of the MO slope and VRE capacity. We likewise confirm this numerically in the following section.

Consider next $k_2 + k_3 = 0$ and thus $b = 0$, corresponding to **Case 1**. The expected value of the plant no longer depends on the VRE capacity and the investment timing problem becomes univariate. Investment is optimal when the MO slope is sufficiently high, i.e. when $M_t = M^*$, where α_M solves

$$\frac{1}{2}\sigma_M^2 \alpha_M(\alpha_M - 1) + \mu_M \alpha_M - \beta = 0$$

and

$$M^* = \frac{I}{a} \cdot \frac{\alpha_M}{\alpha_M - 1}.$$

Note that

$$\frac{dM^*}{d\mu_M} = -\frac{I}{a^2} \cdot \frac{\alpha_M}{\alpha_M - 1} \cdot \frac{da}{d\mu_M} - \frac{I}{a} \cdot \frac{1}{(\alpha_M - 1)^2} \cdot \frac{d\alpha_M}{d\mu_M},$$

where $a, I > 0$, $\alpha_M > 1$ and $da/d\mu_M > 0$ and $d\alpha_M/d\mu_M < 0$. Thus, M^* is increasing with μ_M if $-a(d\alpha_M/d\mu_M) > \alpha_M(\alpha_M - 1)(da/d\mu_M)$ and otherwise non-increasing. Without merit order and cannibalization effects, a higher drift of the MO slope may likewise slow down or accelerate investment, depending on the current drift. Furthermore,

$$\frac{dM^*}{d\sigma_M} = -\frac{I}{a} \cdot \frac{1}{(\alpha_M - 1)^2} \cdot \frac{d\alpha_M}{d\sigma_M},$$

where $d\alpha_M/d\sigma_M < 0$ such that M^* is increasing with σ_M. As above, a higher volatility of the MO slope always defers investment.

5.2. Numerical example

Fig. 4 shows the investment thresholds for the slope of the MO curve. Without VRE merit-order effect and cannibalization (**Case 1**), we use the univariate problem and depict the MO threshold, M^*. With the merit-order effect but without cannibalization (**Case 2**) and for the full model (**Case 3**), respectively, we make use of the bivariate problem and illustrate the threshold for a given level of VRE capacity, $M^*(W)$. Investment is optimal when the slope is at or above its threshold. For reference, we also show the initial slope of the MO curve, m_0. Since this is below the thresholds for most parameter values, it is not optimal to invest immediately, but rather to postpone investment.

In the absence of merit-order effect and cannibalization, the impact of an increase in the drift of the MO slope can be divided into two (top right, purple line). On one hand, it increases the project value, as shown in the previous section, requiring a lower MO slope at the time of investment to achieve the same project value. On the other hand, it also raises the option value, and thus, requires a higher MO slope to justify investment. The former effect dominates for low MO growth rates and vice versa for high growth rates.

The effect prevails in the presence of merit-order effect and/or cannibalization (teal and yellow lines), although the threshold curves shifts upward and to the right. In these cases, the increase in the project value as a result of an increase in drift is less pronounced than if merit-order effects and cannibalization are ignored, and hence, when the change in project value dominates the threshold is higher (teal and yellow lines are above purple line). The increase in the value of the option is likewise less pronounced, and when the change in option value dominates the threshold is lower (teal and yellow lines are below purple line). We conclude that by ignoring merit-order effects and/or cannibalization, investment rates may for some drifts of the MO slope be too low, for others too high.

Similarly, the impact of an increase in the drift of the VRE capacity (top left) can be divided into two. It will reduce the project value and the option value, justifying a higher and lower capacity to trigger investment, respectively. As a result, the threshold is decreasing for some drifts and increasing for other, in the presence of merit order effect and/or cannibalization (teal and yellow lines). By ignoring any feedback of VRE on the price (purple), however, the threshold is unaffected by the growth in VRE capacity. By ignoring the merit order effect and/or cannibalization in this particular numerical example, the threshold will always be too low and investment rates will always be too high.

As expected, an increase in volatility will raise the option value and thereby also the threshold, i.e. increasing uncertainty slows down investment. The threshold is increasing in the volatility of both the MO curve and the VRE capacity. In particular, the investor will postpone investment to wait for a steeper MO curve or a lower VRE capacity (although a positive drift of VRE capacity makes this less likely), and consequently higher electricity prices. By ignoring the merit-order effect and/or cannibalization in this particular numerical example, investment rates will always be too high. As for the growth, by ignoring any feedback of VRE on the price, investment rates are unaffected by the volatility of VRE capacity.

For comparison, Fig. E.6 in Appendix E shows the thresholds if the investment decision is based on the break-even according to net present value (NPV) rather than the real options value (ROV). According to the NPV rule, immediate investment is optimal if the NPV is positive. The NPV threshold is always less than the ROV threshold. In fact, it can be seen that NPV suggests immediate investment for many more parameter values than ROV, and so, there is a high risk of making poor investment decisions by disregarding the timing aspect. This is particularly pronounced in the presence of both the merit-order effect and cannibalization.

6. Discussion and conclusion

This paper introduces a conceptual and mathematical framework to account for the merit order and cannibalization effects on VRE assets' revenues. These effects have been subject to extensive debate within the economic and engineering literature [7,8,10,12–14,18], but have been absent from assessments of investments in variable renewables. By conceptualizing the merit-order and cannibalization effects and providing analytic representations of them, we seek to incorporate observations from descriptive economics and energy system modeling into investment decisions. Our approach considers that there is substantial uncertainty about the future development of the capacity mix, as well as the fuel and carbon prices, which in our model are represented through the random walks of VRE capacity and the MO curve. Our results echo that the investor's belief about e.g. VRE capacity growth greatly affects the assessment of investment profitability and optimal timing. Thus, the contribution of this work is to understand better the cannibalization effect, which may ultimately ensure a more adequate investment environment for VRE assets.

While increasing uncertainty and deteriorating revenues over the life-time of real assets have already been addressed in an investment setting [44], we specify these mechanisms in the case of VRE investment. Our stylized model accounts for the correlation between VRE penetration level and price, and yields closed-form expressions for the expected value and variance of revenues' net present value. Moreover, we illustrate how to use the analytical model in a real options framework for an investment timing problem. Previous literature on uncertainties for VRE investments [20–28] has not considered the cannibalization effect in the assessment of revenues.

In addition to showing the qualitative behavior of NPV and Real Options valuations, we use numerical examples to illustrate how the future evolution of market conditions, i.e. the capacity of VRE and the cost structure of dispatchable plants, could affect the expected revenue and risk of VRE investment. These illustrations show quantitative impact from merit-order and cannibalization effects on the short-term revenues for VRE similar to results of numeric simulations with more realistic models of the power market [12,18]. For instance, our estimated impact of cannibalization on short-term revenue (−44% at a penetration level of around 30%) is corroborated by the results in Refs. [12,18].

For the impact on *life-time* revenue and risk, we found no points of reference in the literature. Although recently gaining some attention in the popular debate on investments [45], to the best of our knowledge, the risk of cannibalization has not yet entered the academic literature on investment under uncertainty. However, our numerical illustrations indicate that cannibalization has a significant impact on expected life-time revenue (Section 4.3) and investment timing (Section 5.2). Our illustrative example of assessing NPV of a wind project in Poland indicates a loss of 800 €/kW, i.e. −40% return on investment (Fig. 3). However, if the MO and cannibalization effects are ignored, the investment calculation yields a profit of 600 €/kW, equaling a 33% return on investment. Thus, disregarding the merit-order- and cannibalization effects can lead to greatly exaggerated revenue estimates, and, therefore unprofitable investments.

It should be noted that, due to discounting, future cannibalization has a relatively smaller impact on the NPV than near-term cannibalization. Thus, even though we observe a substantial impact on lifetime revenues, the effect on lifetime revenue from an end-of-lifetime penetration level of e.g. 50% will be smaller than the effect on short-term revenue from a penetration level of 30%. This explains why our estimates of lifetime revenue loss due to cannibalization are smaller than the short-term estimates in the existing literature [7,8,10,12–14,18]. A higher discount rate than the modest 5% applied here would further decrease the effect of future cannibalization on estimated lifetime revenues.

The investment timing example (Section 5) shows that the presence of MO and cannibalization likewise induces different no-loss and optimally timed decisions, thus stressing the importance of incorporating the risk of cannibalization into more advanced methods for capital budgeting. For the Polish wind power project, the MO and cannibalization effects result in higher investment thresholds, and thus, slow down investment. Disregarding these effects, therefore, accelerates investment beyond what is profitable.

There are some obvious limitations of our model, as stated already in Section 2.1. We disregard the seasonal variation of VRE generation, the variability of demand, and in particular the correlation between the demand and the VRE generation.[7] The model omits trade and electricity storage, the consideration of which would weaken the correlation between the investor's VRE generation and the net demand, and hence the price. The model is strictly valid only for VRE capacities less than or equal to the demand, as a higher VRE capacity can produce negative prices with the affine price function. In practical terms, this would allow VRE to generate only 20%–40% of annual energy. The impact of this limitation is further discussed in Appendix F, showing a relatively minor effect in our calculated examples. Similar to other economic models, our model may be viewed as a way of thinking about the

[7] The wind generation in Europe is for instance higher in winter, as is the demand.

Table A.5
Capacities, conversion efficiencies and emission factors.

Technology	Capacity (GW)	Conversion efficiency	Emission factor (tonne CO_2/MWh)
Wind	5.77	N/A	0
Solar	0.56	N/A	0
Hydro	2.39	N/A	0
Lignite	8.05	0.35	0.40
Hard coal	19.20	0.40	0.34
Natural gas	2.97	0.50	0.20

Table A.6
Fuel costs and variable Operation and maintenance (O& M) costs.

Technology	Fuel cost (€/MWh)	Variable O&M (€/MWh)
Wind	0	0
Solar	0	0
Hydro	0	15
Lignite	3	5
Hard coal	11.5	5
Natural gas	25	6

Table A.7
Total operational costs for the technologies in the Polish electricity mix in 2018. The costs are computed using the fuel- and variable O&M costs of Table A.6 and conversion efficiencies and emissions factors from Table A.5. The cost to emit CO_2 is set to 25 €/tonne CO_2.

Technology	Total operational cost (€/MWh)
Wind	0
Solar	0
Hydro	15
Lignite	42
Hard coal	55
Natural gas	66

problem of cannibalization, rather than a prediction about the future. While we have taken care to find reasonable values for the parameters, there is certainly room for further research applying the model to a more realistic setting with the possibility to verify or falsify the validity of some of the assumptions. Our paper illustrates the potential usage of our closed-form expressions for an investment timing problem, but we believe that the analytical framework may also be incorporated into other techniques. As we present closed-form expression for both expected revenues and variance (Eqs. (6) and (8)), the approach could be applied directly in modern portfolio theory. In this regard, further work is required to produce similar expressions for investments into dispatchable generation, allowing for a consistent portfolio model with a broader mix of generating technologies.

We conclude that:

- It is important to incorporate a representation of the cannibalization effect into capital budgeting methods for the electricity sector. Our results show that considering cannibalization has significant qualitative and quantitative implications for Net Present Value (NPV) and Real Options valuations of investments in VRE. From the investor's perspective, the cannibalization effect has a potentially large impact on decreasing the returns to investment, which has already been observed in the market [9,11].
- Our framework provides a way to consider the cannibalization effect in analytical models and thus quantify VRE investments' expected revenues, risk, and investment timing. Moreover, the Real Options example provided here shows that the impact is complex (not monotonous) and that intuition may lead to poor investment decisions.

The conceptual model introduced here may spur future research on the impact on optimal investments and investment behavior in VRE, both from an investor's- as well as from a policymaker's perspective.

CRediT authorship contribution statement

L. Reichenberg: Conceptualization, Methodology, Formal analysis, Writing – original draft, Writing – review & editing. **T. Ekholm:** Conceptualization, Methodology, Formal analysis, Visualization, Writing – original draft, Writing – review & editing. **T. Boomsma:** Methodology, Formal analysis, Visualization, Writing – original draft, 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.

Data availability

Data will be made available on request.

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Appendix A. Additional data

To construct the linearization of the MO curve for dispatchable technologies in Section 2.1, we used data for capacities and compute the operational costs of the technologies present in the Polish electricity mix as of 2018. The EU-ETS price was assumed to have a starting value of 25 €/tonne. The operational cost is the sum of fuel cost (Fuel cost/Conversion efficiency), the variable O&M cost and the cost to emit CO_2 (EU-ETS price × emission factor). The resulting variable costs are listed in Table A.7.

The values to compute the LCOE of wind [€/MWh] and the NPV of wind investment [€/kW] that are used for comparison with the revenues are computed with the values for investment cost, lifetime and discount rate in Table A.8.

Appendix B. Derivation of the variance of revenues

The variance of the net present value of revenues is given by

$$Var(w_0, m_0) = E^{w_0,m_0}_{G,W,M}\left[\left(\int_0^T e^{-\beta t} R(G_t, W_t, M_t)dt\right)^2\right] - E^{w_0,m_0}_{G,W,M}\left[\int_0^T e^{-\beta t} R(G_t, W_t, M_t)dt\right]^2 \tag{B.1}$$

The last term is the square of (6), so it remains to find an expression for the first term:

$$E^{w_0,m_0}_{G,W,M}\left[\left(\int_0^T e^{-\beta t} R(G_t, W_t, M_t)dt\right)^2\right] \tag{B.2}$$

Table A.8
Data on costs and other parameters used to calculate LCOE and costs.

Technology	Investment cost [€/kW]	Fixed O&M [€/kW/year]	Lifetime [years]	Discount rate [%]	Capacity factor
Wind	1200	40	25	5	0.31
Solar	800	30	25	5	0.15

$$
\begin{aligned}
&= E^{w_0,m_0}_{G,W,M}\left[\int_0^T e^{-\beta t}R(G_t,W_t,M_t)dt\int_0^T e^{-\beta s}R(G_s,W_s,M_s)ds\right]\\
&= E^{w_0,m_0}_{G,W,M}\left[\int_0^T\int_0^T e^{-\beta(t+s)}R(G_t,W_t,M_t)R(G_s,W_s,M_s)dsdt\right]\\
&= 2\int_0^T\int_t^T e^{-\beta(t+s)}E^{w_0,m_0}_{G,W,M}\left[R(G_t,W_t,M_t)R(G_s,W_s,M_s)\right]dsdt\\
&= 2\int_0^T\int_t^T e^{-\beta(t+s)}E^{w_0,m_0}_{W,M}\\
&\times\left[(k_1M_t-(k_2+k_3)M_tW_t)(k_1M_s-(k_2+k_3)M_sW_s)\right]dsdt\\
&= 2\int_0^T\int_t^T e^{-\beta(t+s)}E^{w_0,m_0}_{W,M}\\
&\times\left[\left(k_1^2M_tM_s-k_1(k_2+k_3)\left(M_tM_sW_s+M_tM_sW_t\right)\right.\right.\\
&+\left.\left.(k_2+k_3)^2M_tM_sW_tW_s\right)\right]dsdt\\
&= 2\int_0^T\int_t^T e^{-\beta(t+s)}\Big(k_1^2E^{m_0}_M\left[M_tM_s\right]-k_1(k_2+k_3)\\
&\qquad\times\left(E^{w_0,m_0}_{W,M}\left[M_tW_sM_s\right]+E^{w_0,m_0}_{W,M}\left[W_tM_tM_s\right]\right)\\
&\qquad+(k_2+k_3)^2E^{w_0,m_0}_{W,M}\left[W_tM_tW_sM_s\right]\Big)dsdt
\end{aligned}
$$

The fourth line takes advantage of integrands' symmetry between t and s. The fifth line takes the expectation with regard to G_t, using the fact that G_t and G_s are independent almost everywhere, i.e. when $t \neq s$.

Next, we need expressions for the expected values on the last line of (B.2). Let $N_t = \ln(M_t)$, i.e. a Brownian motion with drift. Using this, $E^{m_0}_M\left[M_tM_s\right] = E^{m_0}_M\left[e^{N_t+N_s}\right]$, which equals the first moment generating function for the random variable $N_t + N_s$. This can be split as $N_t + N_s = 2N_t + (N_s - N_t)$. As $s \geq t$, the two terms are independent, and $E^{m_0}_M\left[e^{N_t+N_s}\right] = E^{m_0}_M\left[e^{2N_t}\right]E^{m_0}_M\left[e^{N_s-N_t}\right]$. This gives

$$
E^{m_0}_M\left[M_tM_s\right] = m_0^2\,e^{(2\mu_M+\sigma_M^2)t}\,e^{\mu_M(s-t)} = m_0^2\,e^{(\mu_M+\sigma_M^2)t+\mu_M s} \tag{B.3}
$$

Similarly, let $U_t = \ln(W_t)$. Then $E^{w_0,m_0}_{W,M}\left[W_tM_tM_s\right] = E^{w_0m_0}_{W,M}\left[e^{U_t+N_t+N_s}\right] = E^{w_0m_0}_{W,M}\left[e^{U_t+2N_t}\right]E^{m_0}_M\left[e^{N_s-N_t}\right]$, based on the independence of $U_t + 2N_t$ and $N_s - N_t$. Using this, and taking into account the dependence between U_t and $2N_t$,

$$
\begin{aligned}
E^{w_0,m_0}_{W,M}\left[W_tM_tM_s\right] &= m_0^2w_0\,e^{(2\mu_M+\mu_W+2\rho_{WM}\sigma_W\sigma_M+\sigma_M^2)t}\,e^{\mu_M(s-t)}\\
&= m_0^2w_0\,e^{(\mu_{WM}+\rho_{WM}\sigma_W\sigma_M+\sigma_M^2)t+\mu_M s}
\end{aligned} \tag{B.4}
$$

Similar results hold for $E^{w_0,m_0}_{W,M}\left[M_tW_sM_s\right]$ and $E^{w_0}_W\left[W_tM_tW_sM_s\right]$, yielding the following expressions that were required for (B.2):

$$
\begin{aligned}
E^{w_0,m_0}_{W,M}\left[M_tM_s\right] &= m_0^2\,e^{(\mu_M+\sigma_M^2)t+\mu_M s}\\
E^{w_0,m_0}_{W,M}\left[M_tW_sM_s\right] &= m_0^2w_0\,e^{(\mu_{WM}+\rho_{WM}\sigma_W\sigma_M+\sigma_M^2)t+\mu_M s}\\
E^{w_0,m_0}_{W,M}\left[W_tM_tM_s\right] &= m_0^2w_0\,e^{(\mu_M+\rho_{WM}\sigma_W\sigma_M+\sigma_M^2)t+\mu_{WM} s}\\
E^{w_0,m_0}_{W,M}\left[W_tM_tW_sM_s\right] &= m_0^2w_0^2\,e^{(\mu_{WM}+\sigma_{WM}^2)t+\mu_{WM} s}
\end{aligned} \tag{B.5}
$$

Let us define shorthands for the constants in the exponents, also accounting for the discount rate β:

$$
\begin{aligned}
p_1 &= \mu_M-\beta\\
p_2 &= \mu_M-\sigma_M^2-\beta\\
p_3 &= \mu_{WM}-\beta\\
p_4 &= \mu_{WM}+\rho_{WM}\sigma_W\sigma_M+\sigma_M^2-\beta\\
p_5 &= \mu_M+\rho_{WM}\sigma_W\sigma_M+\sigma_M^2-\beta\\
p_6 &= \mu_{WM}+\sigma_{WM}^2-\beta
\end{aligned} \tag{B.6}
$$

Using (B.5) and (B.6) in (B.2), then inserting (6) and (B.2) into (B.1), and finally solving the integrals gives a closed-form expression for the variance:

$$
\begin{aligned}
Var(w_0,m_0) = 2m_0^2\Bigg(&k_1^2\,\frac{p_2+p_1e^{(p_1+p_2)T}-(p_1+p_2)e^{p_1T}}{p_1p_2(p_1+p_2)}\\
&-w_0k_1(k_2+k_3)\,\frac{p_4+p_1e^{(p_1+p_4)T}-(p_1+p_4)e^{p_1T}}{p_1p_4(p_1+p_4)}\\
&-w_0k_1(k_2+k_3)\,\frac{p_5+p_3e^{(p_3+p_5)T}-(p_3+p_5)e^{p_3T}}{p_3p_5(p_3+p_5)}\\
&+w_0^2(k_2+k_3)^2\,\frac{p_6+p_3e^{(p_3+p_6)T}-(p_3+p_6)e^{p_3T}}{p_3p_6(p_3+p_6)}\Bigg)\\
&-m_0^2\left(k_1\frac{1-e^{-p_1T}}{p_1}-w_0(k_2+k_3)\frac{1-e^{-p_3T}}{p_3}\right)^2
\end{aligned} \tag{B.7}
$$

Appendix C. Real options derivations

With an infinite option, we obtain a time-homogeneous value process. As a result, the dynamic programming recursion of (10) is

$$
F(W,M) = \max\left\{V(W,M),\,\frac{1}{1+\beta dt}E[F(W+dW,M+dM\mid W,M)]\right\}.
$$

where W and M refer to the current levels of VRE capacity and the MO slope, respectively. According to this recursion, at any point in time, the investor may undertake investment and realize its value or decide to defer. The decision depends on the trade-off between the current expected value of the plant and the discounted expected future value of the option to invest.

When it is optimal to defer investment, this means

$$
E[dF(W+dW,M+dM\mid W,M)] = \beta F(W,M)dt.
$$

Using Ito's Lemma to expand the left-hand-side, we obtain the partial differential equation (PDE)

$$
\begin{aligned}
&\frac{1}{2}\left(2\rho_{WM}\sigma_W\sigma_M WM\frac{\partial^2F}{\partial W\partial M}+\sigma_W^2W^2\frac{\partial^2F}{\partial W^2}+\sigma_M^2M^2\frac{\partial^2F}{\partial M^2}\right)\\
&\quad+\mu_W W\frac{\partial F}{\partial W}+\mu_M M\frac{\partial F}{\partial M}-\beta F = 0.
\end{aligned}
$$

This is subject the boundary conditions

$$
\begin{aligned}
&F(W,M) = V(W,M)-I,\ \frac{\partial F}{\partial W} = -bM\ \ \frac{\partial F}{\partial M} = a-Wb\\
&\lim_{M\to 0}F(W,M) = 0,\ \lim_{W\to\infty}F(W,M) = 0
\end{aligned}
$$

i.e., when it is optimal to invest, the net present value of the plant is realized, and when the slope of the merit order curve tends to zero or the VRES capacity to infinity, the investment is worthless.

To obtain a solution to the PDE, we assume that $F(W,M) = AW^{\alpha_W}M^{\alpha_M}$ with $\alpha_W < 0 < 1 < \alpha_M$. Then, α_W,α_M satisfy

$$
\begin{aligned}
&\frac{1}{2}\left(2\rho_{WM}\sigma_W\sigma_M\alpha_W\alpha_M+\sigma_W^2\alpha_W(\alpha_W-1)+\sigma_M^2\alpha_M(\alpha_M-1)\right)\\
&\quad+\mu_W\alpha_W+\mu_M\alpha_M-\beta = 0.
\end{aligned} \tag{C.1}
$$

Moreover, at the boundary, W, M and A satisfy

$$
\begin{aligned}
&AW^{\alpha_W}M^{\alpha_M} = M(a-Wb)-I,\\
&\alpha_W AW^{\alpha_W-1}M^{\alpha_M} = -bM,\ \alpha_M AW^{\alpha_W}M^{\alpha_M-1} = a-Wb.
\end{aligned} \tag{C.2}
$$

The solution to (C.1) and (C.2) is given in (11) and (12). Equivalently, for an observed level of VRE capacity, i.e. for fixed W, we refer to (13) and (14).

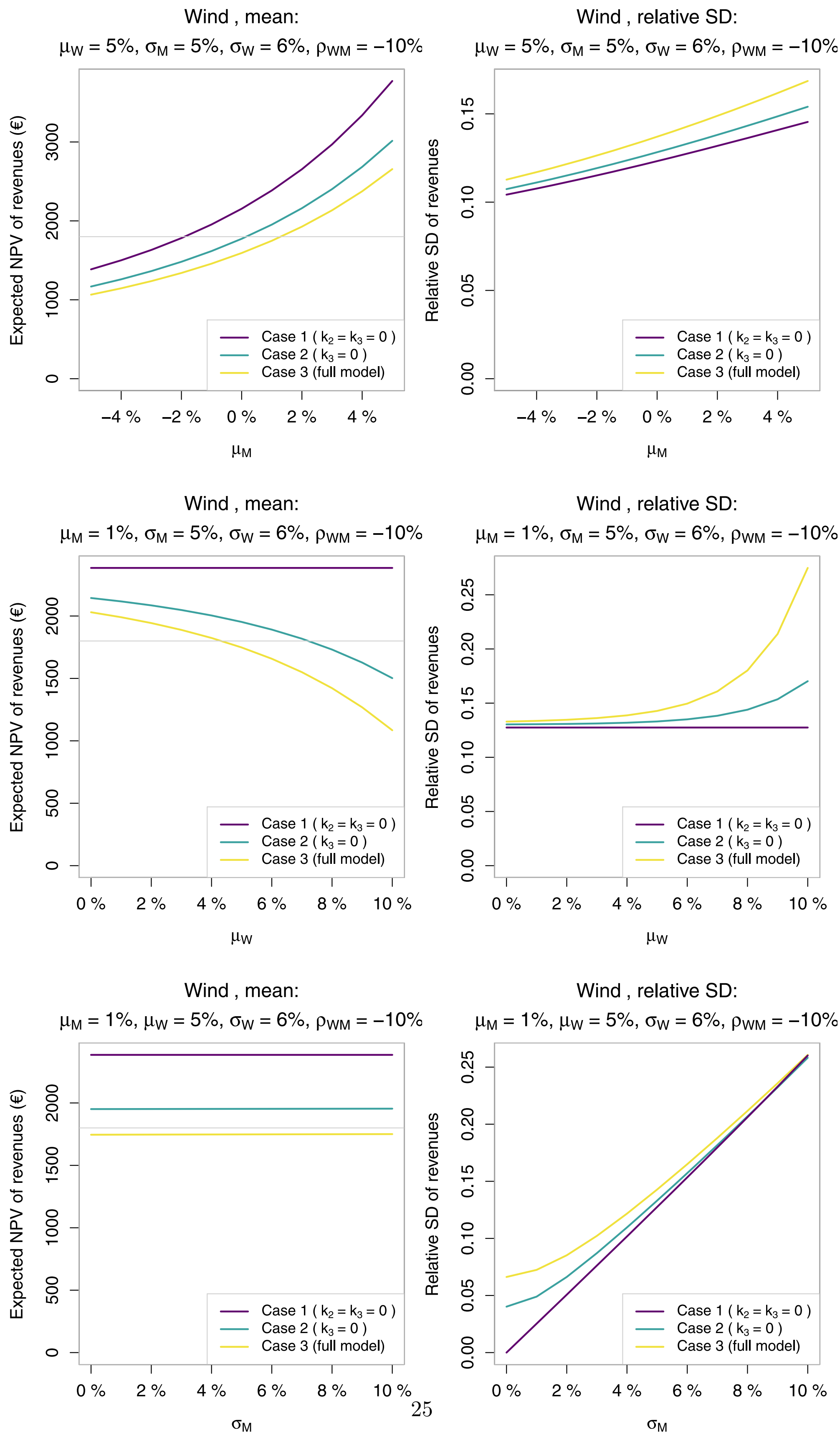

Fig. E.5. The expected value (left) and standard deviation (right) of revenues' NPV for a 1 kW wind power investment with different values of μ_M, μ_W, σ_M, σ_W, ρ_{MW} (x-axis). Different colors indicate full model (yellow), omitting cannibalization (teal) and omitting VRE merit order effect and cannibalization (purple). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

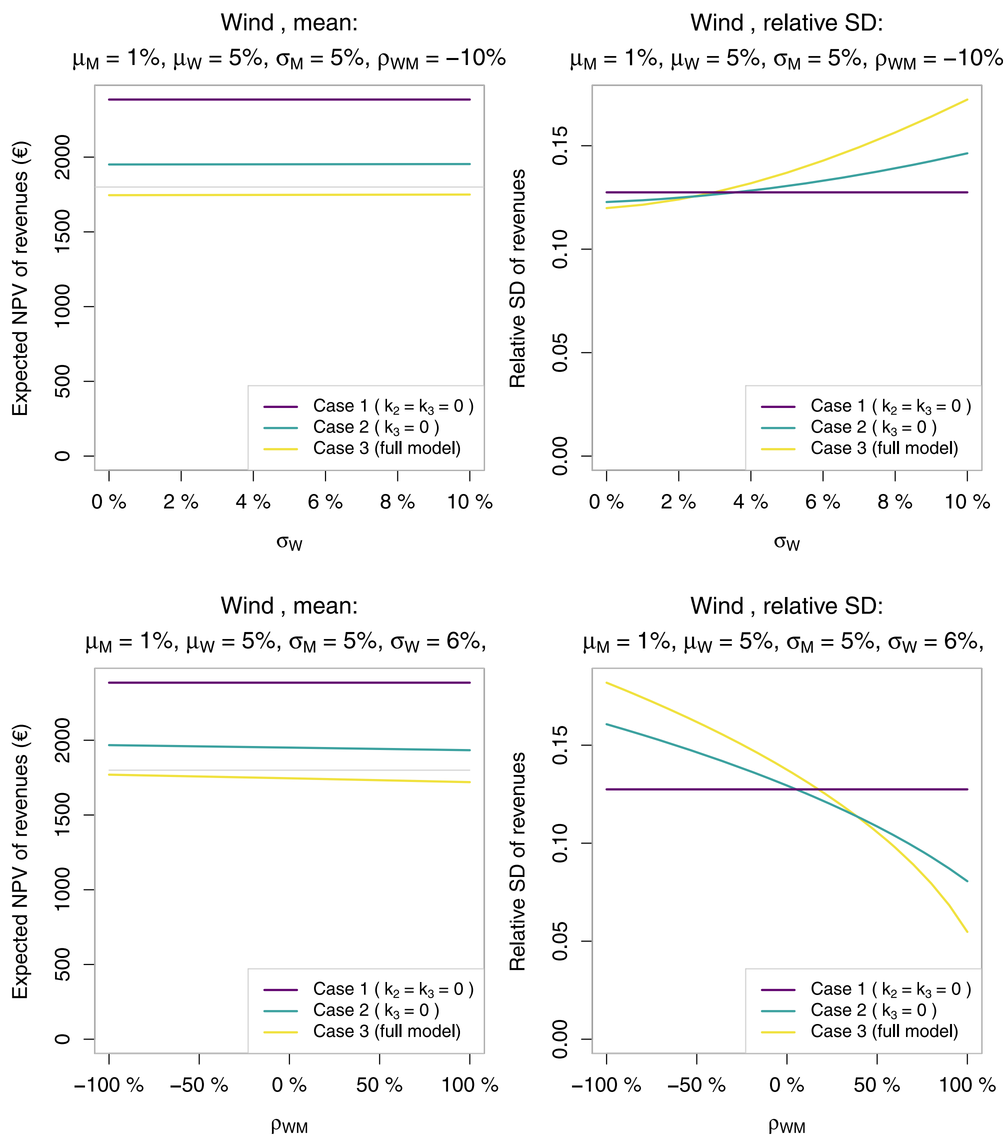

Fig. E.5. (*continued*).

Alternatively, for an observed slope of the MO curve, i.e. for fixed M, α_W solves

$$-\frac{1}{2}\left(2\rho_{WM}\sigma_W\sigma_M\left(\frac{I}{Ma-I}\right)-\sigma_W^2-\sigma_M^2\left(\frac{I}{Ma-I}\right)^2\right)\alpha_W(\alpha_W-1)$$
$$+\left(\frac{1}{2}\left(2\rho_{WM}\sigma_W\sigma_M-\sigma_M^2\left(\frac{I}{Ma-I}\right)\left(\frac{Ma}{Ma-I}\right)\right)+\mu_W-\mu_M\left(\frac{I}{Ma-I}\right)\right)\alpha_W$$
$$+\frac{1}{2}\sigma_M^2\left(\frac{I}{Ma-I}\right)\left(\frac{Ma}{Ma-I}\right)+\mu_M\left(\frac{Ma}{Ma-I}\right)-\beta=0$$

and

$$W^*(M)=-\frac{Ma-I}{Mb}\cdot\frac{\alpha_W}{1-\alpha_W}.$$

Appendix D. Comparative statics

Note that $d\alpha_M/d\mu<0$ and $d\alpha_M/d\sigma<0$, where

$$\mu=\frac{1}{2}\left(-2\rho_{WM}\sigma_W\sigma_M\left(\frac{Wb}{a-Wb}\right)+\sigma_W^2\left(\frac{Wb}{a-Wb}\right)\left(\frac{a}{a-Wb}\right)\right)-\mu_W\left(\frac{Wb}{a-Wb}\right)+\mu_M,$$

$$\sigma=\frac{1}{2}\left(-2\rho_{WM}\sigma_W\sigma_M\left(\frac{Wb}{a-Wb}\right)+\sigma_W^2\left(\frac{Wb}{a-Wb}\right)^2+\sigma_M^2\right),$$

and so,

$$\frac{d\alpha_M}{d\mu_M}=\frac{d\alpha_M}{d\mu}\cdot\frac{d\mu}{d\mu_M}=\frac{d\alpha_M}{d\mu}<0$$
$$\frac{d\alpha_M}{d\mu_W}=\frac{d\alpha_M}{d\mu}\cdot\frac{d\mu}{d\mu_W}=-\frac{d\alpha_M}{d\mu}\cdot\left(\frac{Wb}{a-Wb}\right)>0$$
$$\frac{d\alpha_M}{d\sigma_M}=\frac{d\alpha_M}{d\sigma}\cdot\frac{d\sigma}{d\sigma_M}+\frac{d\alpha_M}{d\mu}\cdot\frac{d\mu}{d\sigma_M}$$
$$=\frac{d\alpha_M}{d\sigma}\cdot\left(\sigma_M-\rho_{WM}\sigma_W\left(\frac{Wb}{a-Wb}\right)\right)-\frac{d\alpha_M}{d\mu}\cdot\rho_{WM}\sigma_W\left(\frac{Wb}{a-Wb}\right)<0$$
$$\frac{d\alpha_M}{d\sigma_W}=\frac{d\alpha_M}{d\sigma}\cdot\frac{d\sigma}{d\sigma_W}+\frac{d\alpha_M}{d\mu}\cdot\frac{d\mu}{d\sigma_W}$$
$$=\frac{d\alpha_M}{d\sigma}\cdot\left(\sigma_M\left(\frac{Wb}{a-Wb}\right)^2-\rho_{WM}\sigma_M\left(\frac{Wb}{a-Wb}\right)\right)+\frac{d\alpha_M}{d\mu}\cdot\left(2\sigma_W\left(\frac{a}{a-Wb}\right)\left(\frac{Wb}{a-Wb}\right)-\rho_{WM}\sigma_M\left(\frac{Wb}{a-Wb}\right)\right)<0,$$

where the first terms of $d\alpha_M/d\sigma_M$ and $d\alpha_M/d\sigma_W$ are negative and the second terms are positive, for $a-Wb>0$ and $\rho_{WM}<0$.

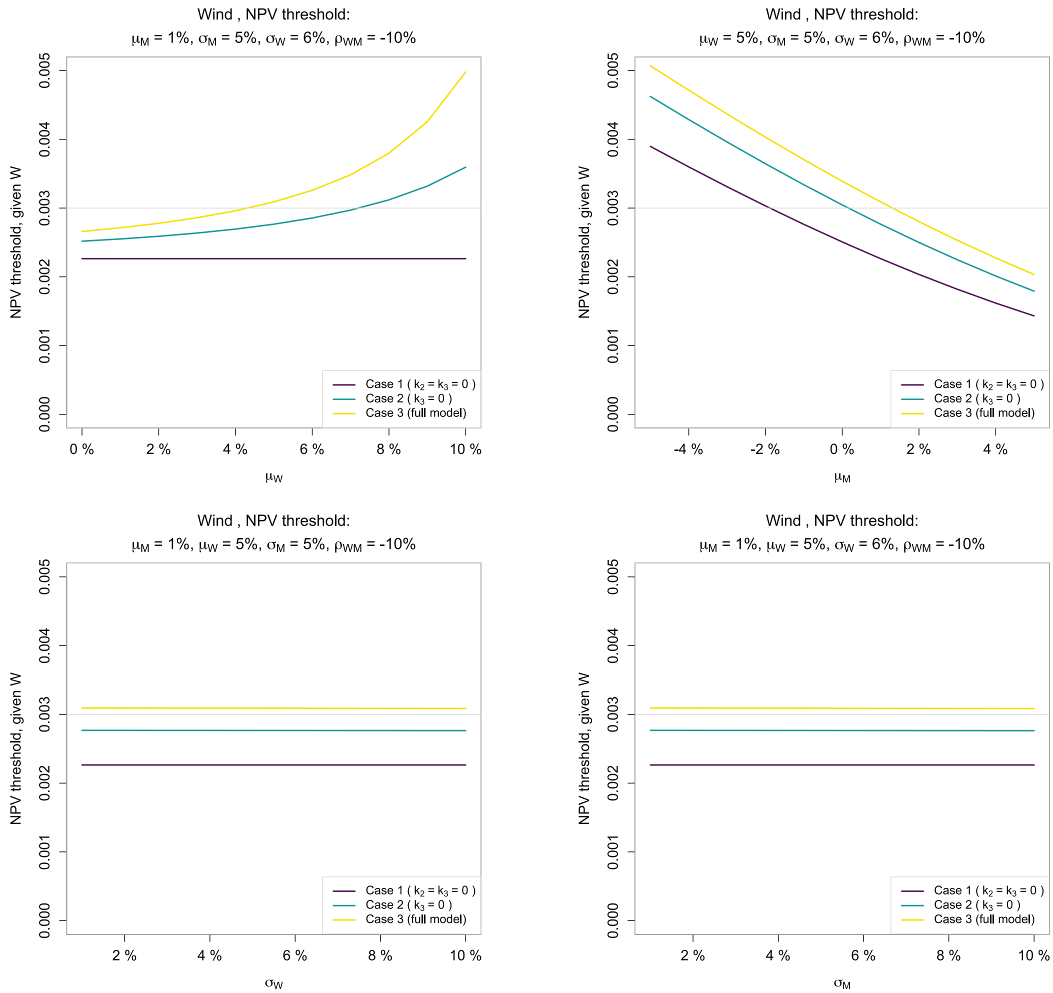

Fig. E.6. Thresholds above which the NPV is positive. For the slope of the MO curve given VRE capacity level (in euros) for 1 MW wind power investment. Thresholds are presented for different values of μ_M and μ_W and standard deviations for σ_M and σ_W along the x-axes. Other parameters are given on top of each figure. Different colors indicate the full model (yellow), omitting cannibalization (teal), and omitting VRE merit-order effect and cannibalization (purple). The gray horizontal lines indicate the initial slope of the MO curve, m_0. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Moreover,

$$\begin{aligned}\frac{d\alpha_M}{db} &= \frac{d\alpha_M}{d\sigma}\cdot\frac{d\sigma}{db} + \frac{d\alpha_M}{d\mu}\cdot\frac{d\mu}{db} \\ &= \frac{d\alpha_M}{d\sigma}\cdot\left(\left(-\rho_{WM}\sigma_W\sigma_M + \sigma_W^2\cdot\frac{Wb}{a-Wb}\right)\cdot\frac{Wa}{(a-Wb)^2}\right) \\ &+ \frac{d\alpha_M}{d\mu}\cdot\left(\left(-\rho_{WM}\sigma_W\sigma_M + \sigma_W^2\cdot\frac{1}{2}\cdot\frac{a+Wb}{a-Wb} - \mu_W\right)\cdot\frac{Wa}{(a-Wb)^2}\right),\end{aligned}$$

where the first term of $d\alpha_M/db$ is negative for $a-Wb>0$ and $\rho_{WM}<0$ and the second term can be positive and negative. For small μ_W, for instance, the second term is negative and so is $d\alpha_M/db$.

Comparative statics with respect to the parameter b may likewise be of interest. Now,

$$\frac{dM^*}{db} = \frac{IW}{a-Wb}\cdot\frac{\alpha_M}{1-\alpha_M} - \frac{W}{a-Wb}\cdot\frac{1}{(1-\alpha_M)^2}\cdot\frac{d\alpha_M}{db},$$

where the first term of dM^*/db is positive for $a-Wb>0$ and the second term can be positive and negative. For small μ_W, for instance, $d\alpha_M/db$ is negative, dM^*/db is positive, and thus, M^* is increasing in b.

Appendix E. Additional numerical results

Fig. E.5 presents the expected revenues and risk as a function all the random walk parameters, thus expanding the results presented in Fig. 3.

Investment thresholds according to the NPV rule are presented in Fig. E.6.

Appendix F. Model validation

The primary issue with model validity is the emergence of negative prices when $G_{A,t}w_t \geq d$, as noted in Section 3. While negative prices have become relatively frequent in markets with a high capacity of VRE [41], stemming from e.g. inflexibility in demand and dispatchable generation and feed-in tariffs for VRE; it is not entirely obvious to which extent they should be present in our framework. With strict interpretation of our modeling framework and an assumption that VRE generation can be curtailed at will when prices go to zero [46], price should be determined by $P_t = \max\{m_t(d - w_t G_{A,t}), 0\}$.

To measure the different in the price formation – i.e. the above formula compared to (1) – we ran a Monte Carlo simulation (sample size 1000, each with 2001 time steps over the VRE plant lifetime) that excludes negative prices as above, and compared thus calculated NPV of revenues to that given by Eq. (6). The results are presented in Fig. F.7. As negative prices become problematic with only a high penetration of VRE, this experiment was done for a range of VRE capacity expansion rates μ_W (as in the numerical examples) and starting level of VRE capacity relative to the demand m_0/d.

Given the initial capacity in the Polish case, VRE capacity expansion rates up to 7.5% produce only minor differences due to negative prices,

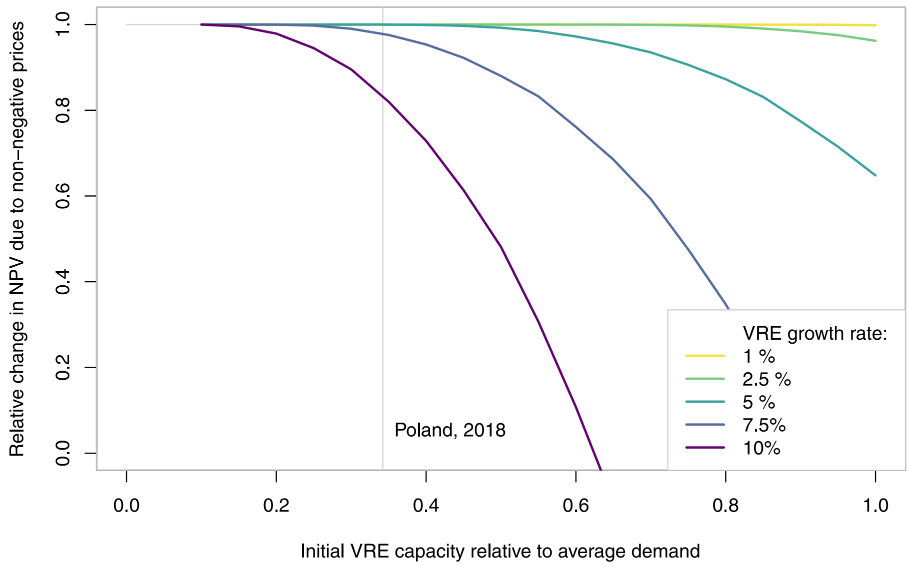

Fig. F.7. Model error due to negative prices. The x-axis presents the initial VRE capacity w_0 relative to the average demand d. The y-axis presents the expected value from Eq. (6) relative to the corresponding result of Monte Carlo simulation that assumes non-negative prices. Colors indicate different rates of aggregate VRE capacity growth μ_W.

but with $\mu_W = 10\%$ the difference is already moderate, but still less than 20%. Therefore one can conclude that the expected revenues in Fig. 3 towards $\mu_W = 10\%$ are slight underestimates if one deems that negative prices should be excluded from the model.

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