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The energy transition and the value of Capacity Remuneration Mechanisms

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ABSTRACT

Capacity Remuneration Mechanisms (CRMs) can be introduced in power markets to address market failures and ensure security of supply. However, investment in capacity is a dynamic process that depends on the evolution of prices and costs over time. In this paper, we investigate the value of capacity under a CRM using a stochastic approach. We focus on three possible technologies participating in the market: a Variable Renewable Energy source, a thermal efficient power plant (such as a Combined Cycle one) and a coal-fired power plant. These three types of capacities can be framed within a common theoretical framework with an increasing level of complexity.

We first present analytical models and then provide sensitivity analysis and calibration results. Our findings indicate that for all three technologies, the effect of the CRM is to cap the firm revenues and consequently to decrease their value. Moreover, the calibration provides a ranking of investments such that carbon emitting plants, in particular gas-fired ones, display higher values compared to renewable ones.

1. Introduction

The energy transition challenge calls an increase in the share of power generation from renewable energy sources. In Europe, for instance, the *Fit for 55* package of the European Commission mandates that by 2030, 65% of electricity in Europe will need to be generated by renewable energy sources, requiring the installation of roughly 450 GW of new renewable capacity.[1] However, the increasing penetration of renewable energy sources, particularly Variable Renewable Energy (VRE) sources, poses challenges to the security of power systems. This is due to the non-controllable nature of VRE sources, leading to higher balancing needs and price volatility (Bonaldo et al., 2022). Meanwhile, controllable back-up capacity, mostly supplied by thermal power plants due to the limited presence of power storage,[2] faces reduced incentives to remain online or be built due to rising investment risks. Thus, there appears to be a trade-off between the growing need for power supplied by VRE and the security of supply challenges this poses to power systems.

One possible approach to reconcile this trade-off involves the implementation of Capacity Remuneration Mechanisms (CRMs) that can favor investments. There exists several types of CRMs (Kozlova et al., 2023; Simoglou and Biskas, 2023; Kozlova and Overland, 2022):

- *capacity payments*, which are payments for capacity administratively set (Genoese et al., 2012);
- *capacity auctions*, procurement auctions through which the System Operator (SO)[3] remunerates a given amount of generation capacity (Yarrow, 2003);
- *reliability options*, contracts sold by power producers to the SO in exchange of a premium, that obliges the seller to supply energy to the power market and return to the SO the extra revenues that they obtain from prices rising above a predetermined level (Andreis et al., 2020);

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[1] Source: https://windeurope.org/wp-content/uploads/files/policy/position-papers/20210317-WindEurope-Fit-for-55-position-paper.pdf.

[2] Clearly, this depends on each specific power system. Power storage at present is mostly provided by means of pumped hydro power storage, due to the high cost and limited capabilities of chemical storage through batteries. Thus, systems that can rely on a high penetration of pumped storage have comparatively less need of back-up capacity. It should also be considered that demand side response can reduce the need to provide thermal back-up capacity, even though at present its role appears to be limited.

[3] In this paper we denote generically as the SO the entity that balances the grid in the short-run and has the responsibility of ensuring security of supply (alone or shared with some other entities). In the USA, it is the Independent System Operators (ISOs), in Europe the Transmission System Operators (TSOs).

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- *capacity obligation*, which is the obligation for load serving entities to hold enough capacity to serve the load (Bowring and Gramlich, 2000);
- *strategic reserves*, which are power plants withdrew from the market and divested to the SO, that uses them whenever there is a security of supply threat (Bhagwat and de Vries, 2013).

Regardless of the specifics of each system, the impact of the introduction of a CRM into power market is to impose *de facto* a price cap to power market: the addition of capacity increases power supplied, preventing electricity prices from spiking to the level of the willingness to pay for the first unit of energy not served (the Value of Lost Load, or VOLL[4]). Thus, the price remains at the level set by the system's marginal cost, i.e., the marginal cost of the last unit of power supplied.[5] Therefore, the marginal cost of the last plant dispatched, i.e., the marginal plant, provides the effective price cap of markets with CRM.

While CRMs can be introduced as a response to the increasing challenges posed to power systems by the energy transition, they have consequences for the evolution of the electricity system (Gerres et al., 2019; Bolton and Clausen, 2019; Höschle et al., 2015). Indeed, by inducing new capacity to come in line, it impedes the power system to benefit from future reduction in investment costs accruing, for instance, from a technological evolution. Thus, a trade-off arises between security of supply and the benefit of technological evolution. In this paper, we explore this trade-off by studying the value of investment in different types of power capacity incentivized by the CRM. To do so, we need to take into account that the value of investment is random. Investors set up power plants under a CRM scheme face several risks. A first source of risk derives from the randomness of power prices. To this, a further risk is added, which arises because of the missed price spikes that would have been observed whenever the load would have been shed, had the CRM not been in place. We can call it a price cap effect. Thus, a second source of randomness derives from the dynamic of the price cap effect; this in turn depends on two factors: on the load and on the marginal cost of the least efficient unit installed (the marginal technology), which will be called in when the system is running short of capacity. There is however a third source of risk, that is related to the technology that the investor chooses at the time of the investment. Indeed, plants are called depending on the merit order, that prescribes calling first plants with the least marginal cost. Thus, the investor needs to forecast to what extent its plant risks to be displaced by some more efficient plant with lower marginal cost that might come in line and push it out of the market for those hours in which its own marginal cost will be too high. This is a technological risk.[6]

Thus, depending on how the different risks combine, it is well possible that different technologies receive distinct incentives to build power plants. This has key consequences for the energy transition. Depending on the incentives and the market design of the CRM, it is possible that carbon neutral technologies are favored or disadvantaged vs. hydrocarbon-fired plants.

Evaluating to what extent a CRM can favor or not the energy transition taking into account explicitly the rigidity in the technology evolution induced by the CRM is therefore of the utmost importance to assess the compatibility of a CRM with the energy transition. This is the purpose of this paper. In order to distinguish between capacity that favor energy transition and capacity that can lock-in the technological evolution, we consider three possible types of capacity participation to CRM:

1. a capacity supplied by VRE source coupled with an efficient Energy Storage System (namely, energy always available when needed without any unavailability risk);
2. a thermal efficient capacity, for instance a Combined Cycle Gas Turbine power plant that represent the state-of-the art of the efficiency at the time of the investment and that will never be surpassed during the life period of the CRM;
3. a capacity that, albeit cheaper at the time of the investment, faces a random marginal cost of generation, that might eventually become more costly than some other installed technology. An example could be a coal fired power plant, for which the generation cost depends on the primary energy price, as well as on the cost of emission abatement or compensation which can increase the cost of power generation.

We shall see that these three types of capacities can be framed within a common theoretical framework, whose level of complexity increases as the uncertainty rises, going from the simplest scheme (the firm VRE) to the most complex one (coal plant with fully random costs).

For these different technological provisions, we consider how to evaluate them, focusing on their Net Present Value, adopting a stochastic approach.

In the following sections, we first provide a theoretical framework, and then we apply the theoretical findings to real markets using plausible time series. In order to measure the value of the investment, we shall calibrate the model using figures from the Italian market. Nevertheless, we highlight that our theoretical results are valid even if different time series are considered, provided that the stochastic underlying processes follow the assumed behaviors. In order to see the consequences of the CRM for the energy transition, we shall measure the impacts of the investments under the CRM by means of a function that shall include both the value of the investments and the social cost of the related carbon emissions.

The paper is structured as follows: Section 2 briefly summarizes the relevant literature. Section 3 provides the analytical framework of the three models, characterized by an increasing level of complexity. In Section 4 we provide the data used for the calibration of the models, and then investment values are calculated and commented. Section 5 presents sensitivity analyses of value function, of each model, with respect to different levels of drift and uncertainty parameters, first, and then with respect to different values of the emission prices. It is followed by final remarks and suggestions for future studies. Proofs of the Propositions and time series analysis are in Appendix.

2. Literature review

A range of studies have explored the design and implementation of CRMs in electricity markets. An introduction and analysis of CRMs can be found, for example, in Creti and Fontini (2019). While a comprehensive review of different CRMs, including capacity payments, strategic reserves, and capacity auctions, is provided by Bublitz et al. (2019) and Finon and Pignon (2008).

Some studies have quantitatively analyzed the option value of power capacity, such as Andreis et al. (2020), Fontini et al. (2021), Khalfallah (2009), and Burger et al. (2004). In Andreis et al. (2020) a semi-explicit formulae to evaluate the option value of a Reliability Option (RO) is provided. The study shows how the value of the RO strictly depends on its parameters such as strike price, volatility rates, and correlation coefficient. The impact of ROs on investment decisions in power generation projects is investigated by Fontini et al. (2021).

[4] For in depth definition of VOLL see Schröder and Kuckshinrichs (2015).

[5] Except for those few hours in which installing extra capacity would imply such a rise in the cost, well above the willingness to pay for those extra hours of energy, making it not be optimal to generate power but it would be more efficient to shed load. This is the optimal level of load shedding. See any textbook of electricity market for this, e.g. Creti and Fontini (2019), Ch. 9.

[6] There can be other sources of uncertainty when an investor chooses to invest in power generation, namely, the one accruing from the capital costs and the uncertainty about the capacity remuneration itself. This will be the case, for instance, of capacity auctions, that are run after that a given investment has been brought in line. In this paper, we shall neglect this, assuming that investment costs in a given power plant are known, even if they differ across technologies. Also the amount of the CRM is known.

Their results suggest that the adoption of an RO scheme can potentially hinder the security of supply by delaying the adoption of new capacity. Khalfallah (2009) adopts a dynamic programming and real option theory to develop two dynamic investment models aimed at addressing long-term capacity adequacy issues in electricity markets. The study compares reliability contracts and capacity obligations as investment incentive mechanisms against the energy-only market. It also explores technology preferences under different incentive mechanisms and discusses the impact of CO2 pricing on investment strategies. Burger et al. (2004), through a Monte Carlo approach, evaluated capacity as a bundle of call options on hourly prices. The study emphasizes the growing importance of accurately assessing the value of embedded options in electricity contracts after the liberalization of electric power markets.

Schiffer and Hans-Wilhelm (2015) examines Europe's transition to a sustainable energy-supply system and its implications for CRMs, emphasizing the need for comparative analyses of various technologies to inform effective generation capacity mixes. However, most studies are focused on a specific technology. Fraunholz et al. (2021) focuses on the capacity value for electricity storage technologies. It is recognized that administratively set parameters in CRMs can introduce biases favoring either conventional power plants or storage technologies. Khan et al. (2018) focuses on Electrical Energy Storage and Demand Response and their impact on consumer-side flexibility options on security of supply, showing that they can reduce the need for centralized Capacity Markets (CMs). They underline the importance of considering the presence of flexibility options in CM design to stimulate their development and enhance system adequacy. Askeland et al. (2017) analyze energy storage systems in both energy-only markets and markets with CRMs, finding that batteries can serve as a cost-effective alternative to thermal power generation.

However, none of the studies conduct a comparative evaluation, based on a stochastic approach, of the different technologies under Capacity Remuneration Mechanisms as we do here. Our methodology computes the Net Present Value of these technologies within a CRM framework that considers investment costs, capacity premium, expected value of operating profits, and emission factor.

3. Analytical framework

We focus on the uncertainty that comes from market operation, namely, the activity of running the power plant and selling electricity in the market, under the CRM scheme, assuming that the investment remains operating with a sufficiently long time scale. For the sake of simplicity, we shall treat it as permanent commitment to generate power, i.e., we assume an infinite horizon.[7]

We shall consider three different technologies, they can be seen as a model with an increasing level of uncertainty about market operation. For the sake of simplicity, we shall assume that all technologies have constant return to scale, which will allow us to focus on the value of the investment regardless of its dimension, i.e. per unit of MW. The first one is a simplified framework in which the investor bears only the power price risk, since it has null marginal cost. This implies that the investor can be sure that throughout the life-time of the plant it will never become the marginal technology.[8] As VRES are characterized by limited controllability and the aim of CRMs is to incentivize capacity that generates energy when needed (otherwise penalties for unavailabilities are set), we suppose that the VRES is coupled to some storage facility, which would allow it to get rid of the cycle of availability of the primary energy, as long as the storage facility is large and reliable enough. Not all types of storage facilities could provide this. Lithium-ion batteries typically have limited capacity supply, specific and constrained charging cycles, are subject to decay and have short expected lifetime. Thus they might not be suitable to participate to the CRM. New forms of storage technologies are emerging that can overcome these limitations. They are termed LDES - Long Duration Energy Storage.[9] In the first model, we are assuming that a LDES storage facility coupled with VRE that can provide long-term energy storage with no decay, for any possible capacity–energy ratio required. This implies that charging and discharging cycles can be planned in advance without any risk of security of supply and with no unavailability risk, as it is the case, for instance, for the Vanadium Redox Flow Batteries (Poli et al., 2024). Thus, the firm VRE capacity can be conceived as equivalent to a thermal power plant with two main differences: no marginal cost of power supply and possibly a larger investment cost. Recall that a CRM that provides (optimal) security of supply implies capping effectively the energy price at the marginal cost of the marginal plant.

Given that the marginal cost of the firm VRE is null, we suppose that the marginal plant under these circumstances would be represented by some other technology, for instance, a thermal power plant. Thus, we shall refer to this marginal cost of the marginal plant as the price cap effect, having in mind that it is effectively the cost of the primary energy fuel that is being generated at the margin when the system is getting short of reserve capacity.

A first degree of complexity is added in the second model as the power capacity has a positive generation cost. This implies two further levels of uncertainty: one given by the evolution of its own cost of power generation which affect revenues; the other one by the price cap effect. Due to this, it can be that over time the own generation cost rises so much that the plant will become the marginal one, even if it was not such at the time of the investment. The first source of uncertainty derives from the price risk while the second one is indeed a quantity risk. For the sake of simplicity, we first rule out the latter, assuming that at the time of the investment the investor is sure that even if its own cost will change over time, there will always be some other power plant whose marginal cost will be higher than its own. Therefore, it will always be dispatched.

For instance, this could be the case of a system which already has installed some thermal power capacity, with a sufficiently long expected life, and in which the new investment is using the same technology but with an advantage in terms of efficiency. In this case, the investor can be sure that its own plant will always be less costly than those other plants. Clearly, to be realistic such an assumption would need to take into account other parameters as well, such as the likelihood that those other plants go offline earlier than the new investment, or that over time new efficient plant come in line and crowd out the investment. Here, we neglect these possibilities for the sake of simplicity and focus on an investment that does not face significant quantity risk from the price cap effect.

To help frame this case, we shall refer to it as the investment in an efficient Combined Cycle Gas Turbine plant in a system that is largely gas-based.

Finally, in the third model we shall consider a technology whose marginal cost is random and that might eventually be displaced by some other more efficient new entrant. The investor therefore will bear three sources of risk: the electricity price risk, its own generation cost risk and the (quantity) risk of becoming marginal. In order to

[7] Even if this is not what occurs in real world, it can be representative of those CRMs that imply a long-run time commitment, such as the 15 years-long time commitment of the Italian auctions for new capacity held in year 2019.

[8] For simplicity we are assuming that even in the case of null system price it has priority dispatch. Moreover, we are not considering here the case of negative marginal price. Such an assumption is not too restrictive in this framework, since normally CRM are implemented when there is a security of supply risk, which implies that the system is short in capacity and thus the system marginal price is positive. In other words, a negative price would imply a system long in capacity, for which there would not be any need of a CRM.

[9] https://www.mckinsey.com/business-functions/sustainability/our-insights/net-zero-power-long-duration-energy-storage-for-a-renewable-grid

derive explicit solutions, we shall assume that the random price and the random cost of the investor are represented by independently distributed random variables. Clearly, in real markets, this might not be the case. For instance, the power price might depend on the cost of the primary energy if the cost of power generated by hydrocarbon can be passed-through to power prices.[10] We do not consider this aspect here.

An example of this can be provided by power generation from coal. For these plants, at the time of the investment the operating cost of power generation might be cheaper than the system marginal cost (where the latter can be given for instance, by gas fired plants). However, these investments bear the risk of its own cost dynamics, which implies that over time coal plants might be crowded out because of the relative dynamic of its own cost and the ones of the other technologies. Nevertheless, we highlight that this is just an example that will help us frame the model and providing plausible figures for the value of the investment. To show all possible cases, we shall also consider different figures for the random cost component, which might be take as proxies for different technologies.

Table 2 reports the list of variables and their meanings used in the models outlined below.

3.1. Model 1: VRE coupled with LDES

In the first model, we have two sources of uncertainty, that we frame as stochastic variables: the day-ahead electricity price, P_t, and the price cap effect, C_t, that we represent as a random variable depending on the marginal cost of the (least efficient) marginal technology, i.e., the technology with the highest marginal cost. The CRM is awarded ex ante to the capacity, being it either administratively set or derived as the equilibrium price of some market mechanism, such as a capacity auction. We do not focus here on how to calculate it or to let emerge its fair value (see Andreis et al., 2020 and references therein) and simply assume that it correspond to a given installment, K, (the capacity premium) expressed in terms of money per capacity per year, attributed ex-ante to the capacity. In addition, since the capacity premium is paid in annuities throughout the whole commitment period, without losing generality, we assume that is paid in full at the beginning of the commitment period.[11]

As mentioned, in this model, there are no variable costs of power generation. The Net Present Value is simply the difference between the Investment costs, net of the premium, and the flow of operating profits accruing from selling energy in the power market, which correspond to the revenues, given that the operating cost null. The operating profits, however are influenced by the existence of the CRM. In particular, two regimes arises. Whenever the system is not tight (i.e., there is enough spare capacity), the price cap effect of the CRM is not binding, and the electricity price is below the marginal cost of the least efficient technology installed (in the sense of the technology with the highest marginal cost). This defines the regime where $P_t < C_t$. Another regime arises when the system would have experienced a load shedding had the CRM not being in place. The latter ensures that there is enough capacity at the margin, and thus the price is given by the marginal cost of the (least efficient) marginal technology. This is the price cap effect, which becomes binding when $P_t \geq C_t$. In Fig. 1, revenues for VRE capacity are represented.

The instantaneous operating profit at time $t \geq 0$ for the investment in VRE capacity must take into account the fact the power plant might not produce for the whole year:

$$\tilde{\pi}_t^{VRE} = \min(P_t,\ C_t) * capfac^{VRE} \tag{1}$$

[10] There exist a large literature on the estimate of electricity costs pass-through, see for instance Caporin et al. (2021) and references therein.

[11] Similarly, we do not consider the lag-time that usually exists between the awarding of the premium and the effective delivery of capacity, and similarly assume that new investments occur instantaneously.

where $capfac^{VRE}$ is the technology-specific (in this case for VRE) capacity factor.[12] They can be converted into a capacity-weighted instantaneously operating profit as follows:

$$\pi_t^{VRE} = \frac{\tilde{\pi}^{VRE}}{capfac^{VRE}} = \min(P_t,\ C_t) \tag{2}$$

Or, more specifically:

$$\pi_t^{VRE} = \begin{cases} C_t & \text{if } P_t \geq C_t \\ P_t & \text{if } P_t < C_t \end{cases} \tag{3}$$

We assume that the day-ahead electricity price P_t and the price cap effect C_t are stochastic and follow a Geometric Brownian Motion (GBM)[13]:

$$\frac{dP_t}{P_t} = \mu_P dt + \sigma_P dW_t^P \quad \text{with } P_0 = P \tag{4}$$

$$\frac{dC_t}{C_t} = \mu_c dt + \sigma_c dW_t^C \quad \text{with } C_0 = C \tag{5}$$

where μ_P and μ_c are drifts of the two processes, σ_P and σ_C are the volatility parameters, and dW_t^P and dW_t^C are the increments of a Wiener process.[14]

The static picture of revenues can be extended to a dynamic (multi-period) setup in order to calculate the expected net present value of the project (NPV). The latter is just the difference between the (deterministic) investment costs[15] net of the capacity premium, i.e. $I^{VRE} - K$, and the expected flow of operating profits accruing from operating the plant and selling electricity in the market. The expected value of the latter is thus given by the following equation:

$$V^{VRE}(P,C) = \mathbb{E}_0 \left[\int_0^{\infty} \min(P_t,\ C_t) e^{-rt} dt \right] \tag{6}$$

where $\mathbb{E}_t(\cdot)$ is the expectation operator taken with respect to the information at $t = 0$ and r is the discount rate.

Standard stochastic dynamic programming methods allows obtaining a close form solution for the value function $V^{VRE}(P,C)$ distinguishing the case in which $P \geq C$ or $P < C$. Provided that $r - \mu_P > 0$ and $r - \mu_C > 0$, the following Proposition summarizes the solution of (6), hereafter we drop the time index when this does not cause confusion.

[12] The capacity factor is the ratio of the energy produced in a given period over the maximum possible producible energy in the same period. It converts a given amount of capacity, that might not be active throughout the whole period, into its equivalent fraction that generates for the whole considered period.

[13] The GBM is largely used in the field of Real Options and renewable energy (see the literature review provided by Kozlova (2017) Kozlova, 2017). Note that also other process, such as a simple Brownian motion (neither arithmetic nor geometric) can represent the main features of the electricity prices (see Borovkova and Schmeck, 2017). Andreis et al. (2020) study how to calculate values of CRM depending on different underlying stochastic processes of the power prices. They show that even though the GBM does not provide a full representation of the electricity price dynamics, it provides a good approximation that enables deriving explicit pricing formulae for the capacity value. Since the aim of our work is to derive closed-form solutions, in order to investigate in depth the impact of CRM on the investment value, we adhere to the perspective provided by Andreis et al. (2020) and adopt the GBM hypothesis accordingly.

[14] We further assume that P_t and C_t are not correlated, i.e., $E(dW_t^P, dW_t^C) = 0$. Such an assumption is plausible, since C_t is the marginal cost of the least efficient unit installed, while P_t is either the marginal cost of the plant that is providing power when there is some spare capacity, or the marginal utility of the first unit that would not be served if the system runs short of capacity.

[15] From now onward, all the superscripts of the parameters refer to the value of the parameter for that specific model, unless differently specified. Thus, for instance, the investment cost for the VRE is denoted as I^{VRE}.

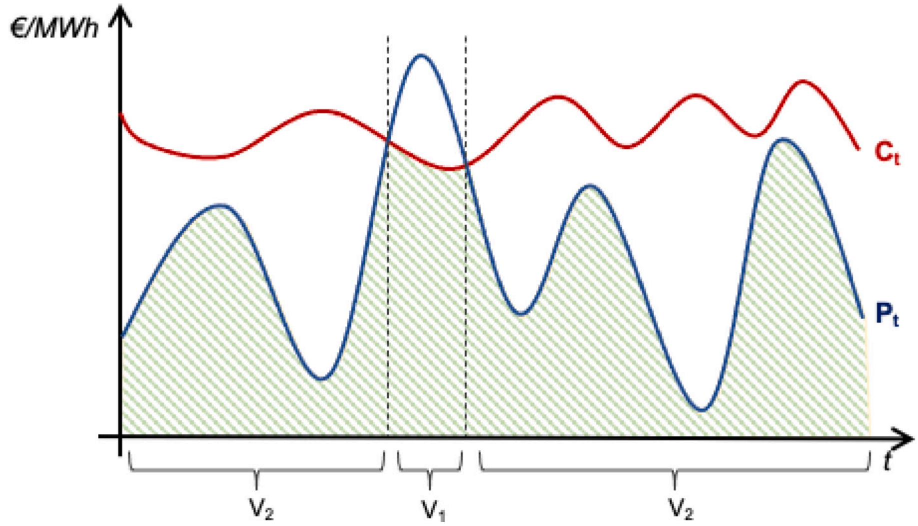

Fig. 1. The green area represents the operating profits for a firm capacity supplied by a VRE in the presence of the CRM. The red line represents the marginal cost of the marginal technology, C_t; the blue line represents the day-ahead electricity prices P_t. The vertical dashed lines identify the regimes of the value function, as described by Eq. (7). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Proposition 1. *The NPV of the investment in the case of VRE is:*

$$\Pi^{VRE}(P,C) = -I^{VRE} + K + V^{VRE}(P,C) * capfac^{VRE}$$

with:

$$V^{VRE}(P,C) = \begin{cases} V_1^{VRE} = \frac{C}{r-\mu_C} + A^{VRE}C^{1+\beta_1}P^{-\beta_1} & \text{for } P \geq C \\ V_2^{VRE} = \frac{P}{r-\mu_P} + B^{VRE}C^{1+\beta_2}P^{-\beta_2} & \text{for } P < C \end{cases} \quad (7)$$

Where:

$$A^{VRE} = \frac{(r-\mu_C) + \beta_2(\mu_P - \mu_C)}{(\beta_2 - \beta_1)(r-\mu_P)(r-\mu_C)} \quad (8)$$

$$B^{VRE} = \frac{(\mu_P - \mu_C)\beta_1 + (r-\mu_C)}{(\beta_2 - \beta_1)(r-\mu_P)(r-\mu_C)} \quad (9)$$

and

$$\beta_1 = -\left(\frac{1}{2} + \frac{\mu_C - \mu_P}{\sigma_C^2 + \sigma_P^2}\right) + \sqrt{\left(\frac{1}{2} + \frac{\mu_C - \mu_P}{\sigma_C^2 + \sigma_P^2}\right)^2 + \frac{2(r-\mu_C)}{\sigma_C^2 + \sigma_P^2}} > 0 \quad (10)$$

$$\beta_2 = -\left(\frac{1}{2} + \frac{\mu_C - \mu_P}{\sigma_C^2 + \sigma_P^2}\right) - \sqrt{\left(\frac{1}{2} + \frac{\mu_C - \mu_P}{\sigma_C^2 + \sigma_P^2}\right)^2 + \frac{2(r-\mu_C)}{\sigma_C^2 + \sigma_P^2}} < 0 \quad (11)$$

Proof. See Appendix A.

Note that $V^{VRE}(P,C)$ is made of two regimes. The first one occurs when the price cap effect is binding, i.e. $P \geq C$. In this regime, the term $\frac{C}{r-\mu_C}$ indicates the discounted sum of the expected operating profits if the price cap effect was binding forever. The second one corresponds to the case in which the price cap effect is not binding, i.e. $P < C$. The discounted sum of the expected profits if this regime was to remain active forever is given by $\frac{P}{r-\mu_P}$.

On the contrary, the terms $B^{VRE}C^{1+\beta_2}P^{-\beta_2}$ and $A^{VRE}C^{1+\beta_1}P^{-\beta_1}$ represent the value of the possibility, due to the existence of the CRM, that when the plant is under one regime it falls into the other, i.e., that the price cap effect becomes binding when it is not or that a reduction of the electricity price below the price cap is observed when the price cap effect is binding.

We refer to these values as the *CRM-induced switching values*, or just *switching values* in brief. The sign of these *switching values* depend on the sign of the constants A^{VRE} and B^{VRE}, which in turns, depend on μ_P, μ_C, β_1 and β_2. Section 3.2 below discusses their value and sign and presents a sensitivity analysis with respect to $r - \mu_P$ and $r - \mu_C$. Calibrations and sensitivity analysis of the value function V^{VRE} with respect to drifts (μ_P and μ_C) and volatility (σ_P and σ_C) terms are also presented.

3.2. Model 2: Efficient CCGT

In this section we deal with the case of a capacity which has a positive marginal cost of generating power. This implies two further levels of uncertainty for a given plant: one given by the evolution of its own power generation cost, and a second one accruing from the price cap effect. Recall that because of the latter, some other more efficient plant might become the marginal one in some hours, crowding-out the power supplied by the current plant. We separate these two cases, and consider first just the possible uncertainty accruing from its own cost evolution (and from the dynamics of the electricity price) without including the risk of becoming the marginal or super-marginal technology because of the evolution of the other plants' costs. In other words, we shall assume that the investor will be sure that, after the investment, its own plant will always be more efficient than some other plant that is installed and therefore has no risk of being crowded-out in the merit order. This will be framed in the model assuming that there is a cost of generating power B_t, but the plant is always more efficient than the plant that will be the marginal one and that will determine the price cap effect, i.e. $B_t = \alpha C_t$, with $\alpha \in (0,1)$.

Note that now three regimes might arise. The first one, as before, is when the price cap effect of the CRM is binding. In this case, the operating profits derive from the difference between the price obtained by selling energy in the power market, which is capped by the price cap effect at the level of C_t, and the own cost of generation αC_t. The second regime occurs when the price cap effect is not binding, thus operating profits derive from the system marginal price P_t, minus the operating costs; this is such only if the price is above the marginal cost of power generation. Finally, whenever it occurs that the system marginal price is so low that the plant cannot recover its own operating cost, we suppose that it can avoid generating power (e.g., remain idle and not bidding in the power market) without any penalty.[16] Thus, in this third regime,

[16] Note that such an assumption is not in contrast with the assumption that selling energy is compulsory for plants that have received CRM, since such a low level of the price implies that there would not be any risk of security of supply. A sufficient condition for this would simply be betting in the day-ahead market at the own marginal cost.

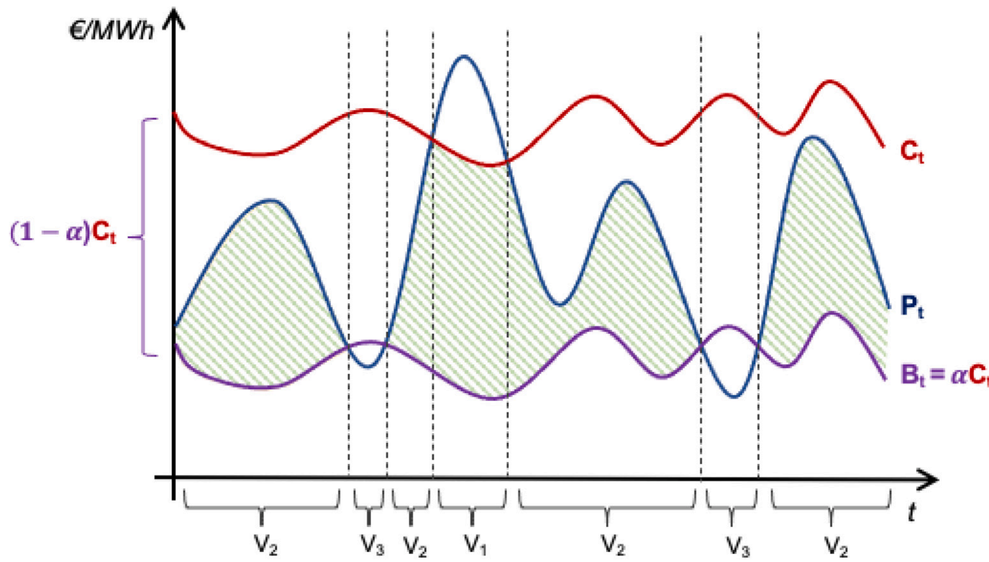

Fig. 2. The green area represents the operating profits for a firm capacity supplied by a CCGT power plant in the presence of the CRM. The red line represents the marginal costs of the marginal technology, C_t; the blue line represents the day-ahead electricity prices P_t; the purple line represents the generation costs for CCGT power plant, αC_t. The vertical dashed lines identify the regimes of the value function, as described by Eq. (16). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

the plant would not generate any operating profits. Fig. 2 represents the operating profits for this type of technology.

The instantaneous operating profits at time $t \geq 0$ for the investment in the CCGT can be written as:

$$\tilde{\pi}_t^{CCGT} = \max[\min(P_t - \alpha C_t,\ C_t - \alpha C_t),\ 0] * capfac^{CCGT} \tag{12}$$

and the capacity-weighted instantaneous operating profits as:

$$\pi_t^{CCGT} = \frac{\tilde{\pi}_t^{CCGT}}{capfac^{CCGT}} = \max[\min(P_t - \alpha C_t,\ C_t - \alpha C_t),\ 0] \tag{13}$$

or, more specifically:

$$\pi_t^{CCGT} = \begin{cases} C_t - \alpha C_t & \text{if } P_t \geq C_t \\ P_t - \alpha C_t & \text{if } \alpha C_t < P_t < C_t \\ 0 & \text{if } P_t < \alpha C_t \end{cases} \tag{14}$$

Note that in the transition from one regime to the other it is assumed that it is not possible to jump from the first regime to the third and vice versa without entering into the second one. The expected value of the operating profits is now:

$$V^{CCGT}(P,C) = \mathbb{E}_0\left[\int_0^\infty \max[\min(P_t,\ C_t) - \alpha C_t,\ 0] e^{-rt} dt\right] \tag{15}$$

Following the same procedure as before, the value function $V^{CCGT}(P,C)$ can be calculated within the three different regimes, i.e. when $P \geq C$, when $\alpha C < P < C$ and finally when $P < \alpha C$. The following Proposition summarizes the solution of (15):

Proposition 2. *The NPV of the investment in the case of capacity supplied by CCGT is:*

$$\Pi^{CCGT}(P,C) = -I^{CCGT} + K + V^{CCGT}(P,C) * capfac^{CCGT}$$

with

$$V^{CCGT}(P,C) = \begin{cases} V_1^{CCGT}(P,C) & \text{for } P \geq C \\ V_2^{CCGT}(P,C) & \text{for } \alpha C < P < C \\ V_3^{CCGT}(P,C) & \text{for } P < \alpha C \end{cases} \tag{16}$$

and

$$V_1^{CCGT}(P,C) = \frac{(1-\alpha)C}{r-\mu_C} + A_1^{CCGT} C^{1+\beta_1} P^{-\beta_1} \tag{17}$$

$$V_2^{CCGT}(P,C) = \frac{P}{r-\mu_P} - \frac{\alpha C}{r-\mu_C} + A_2^{CCGT} C^{1+\beta_1} P^{-\beta_1} + B_2^{CCGT} C^{1+\beta_2} P^{-\beta_2} \tag{18}$$

$$V_3^{CCGT}(P,C) = B_3^{CCGT} C^{1+\beta_2} P^{-\beta_2} \tag{19}$$

Where the four constants are given by:

$$A_1^{CCGT} = \frac{(r-\mu_C) + \beta_2(\mu_P - \mu_C)}{(\beta_2-\beta_1)(r-\mu_P)(r-\mu_C)}(1-\alpha^{\beta_1+1}) \tag{20}$$

$$A_2^{CCGT} = -\frac{(r-\mu_C) + \beta_2(\mu_P - \mu_C)}{(\beta_2-\beta_1)(r-\mu_P)(r-\mu_C)}\alpha^{\beta_1+1} \tag{21}$$

$$B_2^{CCGT} = \frac{(r-\mu_C) + \beta_1(\mu_P - \mu_C)}{(\beta_2-\beta_1)(r-\mu_P)(r-\mu_C)} \tag{22}$$

$$B_3^{CCGT} = \frac{(r-\mu_C) + \beta_1(\mu_P - \mu_C)}{(\beta_2-\beta_1)(r-\mu_P)(r-\mu_C)}(1-\alpha^{\beta_2+1}) \tag{23}$$

and β_1 and β_2 are given by (10) and (11) respectively.

Proof. See Appendix B.

In Eqs. (17) and (18) the investment value is composed of two components in each regime. The first one given by the expected discounted flow of operating profits if the value is bound to remain in that regime forever, and the second part is the *switching value* of falling into the other regimes. However, differently from Eq. (A.13), there are now two *switching values* when the plant is in regime two: the electricity price can rise, making the price cap effect binding, i.e., entering into regime one; or the electricity price falls below the marginal cost of the efficient CCGT, i.e., entering into the third regime. The value of the third regime (19) is however given only by the *switching value*. As in this regime the power plant is idle due to costs that are higher than revenues, the switching value is a call option — or the possibility to re-start the electricity production if things would change in the future.

Note also that there is a sort of symmetry with respect to Model 1:

$$A_1^{CCGT} = A^{VRE}(1-\alpha^{\beta_1+1}) \tag{24}$$

$$A_2^{CCGT} = -A^{VRE}\alpha^{\beta_1+1} \tag{25}$$

$$B_2^{CCGT} = B^{VRE} \tag{26}$$

$$B_3^{CCGT} = B^{VRE}(1-\alpha^{\beta_2+1}) \tag{27}$$

i.e. the Model 2 collapses to Model 1 when $\alpha = 0$.

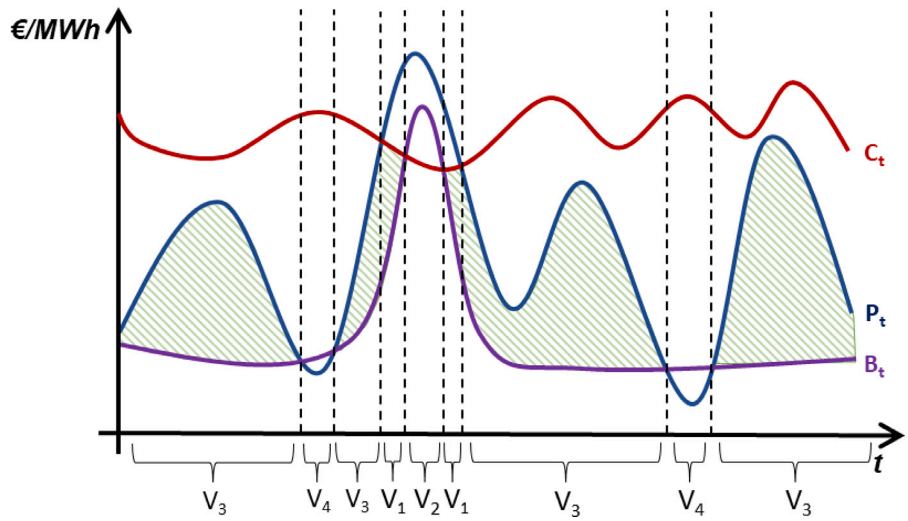

Fig. 3. The green area represents the operating profits for a firm capacity supplied by a Coal power plant under the existence of the CRM. The red line represents the marginal costs of the marginal technology, C_t; the blue line represents the day-ahead electricity prices P_t; the purple line represents the generation costs for Coal power plant, B_t. The gray dashed lines identify the four regimes of the value function as described by Eq. (33). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Section 3.2 will discuss the signs of the four constants A_1^{CCGT}, A_2^{CCGT}, B_2^{CCGT} and B_3^{CCGT}, and present a sensitivity analysis w.r.t. the drift parameters. Calibrations and sensitivity analysis of the value function V^{CCGT} with respect to drifts (μ_P and μ_C) and volatility (σ_P and σ_C) terms are also presented.

3.3. Model 3: coal power plant

In the most general model we assume that all three variables P_t, C_t and B_t are stochastic, with the law of motion of P_t given by Eq. (4), C_t by Eq. (5) and B_t given by[17]:

$$\frac{dB_t}{B_t} = \mu_B dt + \sigma_B dW_t^B \quad \text{with } B_0 = B \tag{28}$$

Now, there can be an inversion in the merit order such that the investment considered might become the marginal technology and be affected by the price cap. As before three regimes arise for the revenues: when the price cap is binding, when it is not binding and the plant is active, which means that the revenues accruing from selling the electricity are higher than the own power generation costs, and when the plant is off. The latter case however can arise for two reasons. Either because the revenues deriving from the power prices would be lower than the cost of power generation, as before, or because the price cap itself changes becoming lower than the own marginal cost. In other words, the own marginal costs might become so high that the plant is crowded out by all other existing plants, even the ones that were more costly before, and thus it is not dispatched anymore. When one of these two states occurs, the plant remains idle. In Figure (Fig. 3) are represented the operating profits for such a technology.

The instantaneous operating profits at time $t \geq 0$ for the investment in the coal-fired plant can be written as:

$$\tilde{\pi}_t^{COAL} = \max[\min(P_t - B_t,\ C_t - B_t), 0] * capfac^{COAL} \tag{29}$$

and the capacity-weighted instantaneous revenue as:

$$\pi_t^{COAL} = \frac{\tilde{\pi}_t^{COAL}}{capfac^{COAL}} = \max[\min(P_t - B_t,\ C_t - B_t), 0] \tag{30}$$

or, more specifically:

$$\pi_t^{COAL} = \begin{cases} C_t - B_t & \text{if } P_t - B_t \geq C_t - B_t \\ P_t - B_t & \text{if } P_t - B_t < C_t - B_t \\ 0 & \text{if } \min(P_t - B_t,\ C_t - B_t) < 0 \end{cases} \tag{31}$$

The expected value of the future discounted operating profits is:

$$V^{COAL}(P, C, B) = \mathbb{E}_0 \left[\int_0^\infty \max[\min(P_t - B_t,\ C_t - B_t), 0] e^{-rt} dt \right] \tag{32}$$

Note that when $B_t = 0$, the problem becomes equal to (6) due to the absorbing nature of zero for the process B_t. Then, here we solve (32) for the general case when $B_t > 0$. However, since the presence of the operating costs B_t in the instantaneous profits function precludes the existence of a closed-form solution, instead of relying on numerical solutions, we proceed by assuming that the investor adopts a simplified strategy. In the specific, we assume that, as it was for the previous cases, the investor chooses not to generate power when P_t and/or C_t are higher than B_t, while it produces if both P_t and C_t are greater than B_t. This identifies 4 regimes: $P \geq C > B$, $B \geq C$, $C > P > B$ and $B \geq P$. In these regimes it is possible to provide analytical solutions for $V^{COAL}(P, C, B)$ as a proxy of (32). The following Proposition summarizes the solution:

Proposition 3. *The NPV of the investment in a Coal power plant is:*

$$\Pi^{COAL}(P, C, B) = -I^{COAL} + K + V^{COAL}(P, C, B) * capfac^{COAL}$$

with

$$V^{COAL}(P, C, B) = \begin{cases} V_1^{COAL}(P, C, B) & \text{if } P \geq C > B \\ V_2^{COAL}(C, B) & \text{if } B \geq C \text{ and } (C - B) < (P - B) \\ V_3^{COAL}(P, C, B) & \text{if } C > P > B \\ V_4^{COAL}(P, B) & \text{if } B \geq P \text{ and } (P - B) < (C - B) \end{cases} \tag{33}$$

and

$$V_1^{COAL}(P, C, B) = \frac{C}{r - \mu_c} - \frac{B}{r} + A_{11}^{COAL} P^{-\eta_1} B^{\eta_1 + 1} + A_{12}^{COAL} P^{-\eta_1} C^{1+\eta_1} + A_{21}^{COAL} C^{1+\eta_2} B^{-\eta_2} \tag{34}$$

$$V_2^{COAL}(C, B) = A_{31}^{COAL} B + A_{32}^{COAL} C^{1+\eta_1} B^{-\eta_1} \tag{35}$$

$$V_3^{COAL}(P, C, B) = \frac{P}{r - \mu_p} - \frac{B}{r} + B_{11}^{COAL} P^{-\eta_1} B^{\eta_1 + 1} + B_{21}^{COAL} C^{1+\eta_2} B^{-\eta_2}$$

[17] We assume that B_t is not correlated with P_t and C_t, i.e. $E(dW_t^B, dW_t^P) = 0$ and $E(dW_t^B, dW_t^C) = 0$.

$$+ B_{22}^{COAL} C^{1+\eta_2} P^{-\eta_2} \quad (36)$$

$$V_4^{COAL}(P,B) = B_{31}^{COAL} B + B_{32}^{COAL} P^{-\eta_2} B^{1+\eta_2} \quad (37)$$

Where the constants are:

$$A_{11}^{COAL} = -\frac{r+\eta_2\mu_p}{(\eta_2-\eta_1)r(r-\mu_p)}, \quad A_{12}^{COAL} = \frac{r-\mu_c+\eta_2(\mu_p-\mu_c)}{(\eta_2-\eta_1)(r-\mu_p)(r-\mu_c)} \quad (38)$$

$$A_{21}^{COAL} = -\frac{r-(1+\eta_1)\mu_c}{(\eta_2-\eta_1)r(r-\mu_c)} \quad (39)$$

$$A_{31}^{COAL} = -\frac{r-\eta_2\mu_p}{(\eta_2-\eta_1)r(r-\mu_p)}, \quad A_{32}^{COAL} = \frac{(1-\eta_1)\mu_p}{(\eta_2-\eta_1)r(r-\mu_p)} \quad (40)$$

$$B_{11}^{COAL} = -\frac{r+\eta_2\mu_p}{(\eta_2-\eta_1)r(r-\mu_p)} \quad (41)$$

$$B_{21}^{COAL} = -\frac{r-(1+\eta_1)\mu_c}{(\eta_2-\eta_1)r(r-\mu_c)}, \quad B_{22}^{COAL} = \frac{r-\mu_c+\eta_1(\mu_p-\mu_c)}{(\eta_2-\eta_1)(r-\mu_p)(r-\mu_c)} \quad (42)$$

$$B_{31}^{COAL} = -\frac{r-(1+\eta_1)\mu_c}{(\eta_2-\eta_1)r(r-\mu_c)}, \quad B_{32}^{COAL} = -\frac{\eta_1\mu_c}{(\eta_2-\eta_1)r(r-\mu_c)} \quad (43)$$

and

$$\eta_1 = -\left(\frac{1}{2}+\frac{\mu_c-\mu_p}{\sigma_c^2+\sigma_p^2}\right)+\sqrt{\left(\frac{1}{2}+\frac{\mu_c-\mu_p}{\sigma_c^2+\sigma_p^2}\right)^2+\frac{2(r-\mu_c)}{\sigma_c^2+\sigma_p^2}} > 0 \quad (44)$$

$$\eta_2 = -\left(\frac{1}{2}+\frac{\mu_c-\mu_p}{\sigma_c^2+\sigma_p^2}\right)-\sqrt{\left(\frac{1}{2}+\frac{\mu_c-\mu_p}{\sigma_c^2+\sigma_p^2}\right)^2+\frac{2(r-\mu_c)}{\sigma_c^2+\sigma_p^2}} < 0 \quad (45)$$

with $p=\frac{P}{B}$, $c=\frac{C}{B}$ *and*

$$\mu_p = \mu_P - \mu_B + \frac{1}{2}\sigma_B^2 \quad (46)$$

$$\sigma_p = \sigma_P - \sigma_B \quad (47)$$

$$\mu_c = \mu_C - \mu_B + \frac{1}{2}\sigma_B^2 \quad (48)$$

$$\sigma_c = \sigma_C - \sigma_B \quad (49)$$

Proof. See Appendix C.

Though the model is more complicate, it is worth noting the symmetry with Model 1. That is, if $B = 0$ the model collapses to Model 1, where $A_{12}^{COAL} = A^{VRE}$ and $B_{22}^{COAL} = B^{VRE}$. Thus, the terms where $B > 0$ indicate the effect of the price of coal on the value of the power plant. For example, $V_2^{COAL}(C,B)$ and $V_4^{COAL}(P,B)$ represent the value of the power plant in the idle state regime with the possibility of restarting when C or P respectively increase above B.

On the contrary, $V_1^{COAL}(P,C,B)$ and $V_3^{COAL}(P,C,B)$ represents the two regimes in which the production plant is operating. In particular, the first regime represents the case in which the price cap induced by CRM is binding, i.e. $P \geq C > B$. Thus, $\frac{C}{r-\mu_c} - \frac{B}{r}$ gives the expected operating profits if the price cap effect was binding forever. The third regime corresponds to the case in which the price effect is not binding, i.e. $C > P > B$. In this case the expected operating profits are given by the discounted value of electricity price, $\frac{P}{r-\mu_c}$, minus the discounted value of power plant costs, namely, the cost of coal. $\frac{B}{r}$. The second part of these equations, $A_{11}^{COAL}P^{-\eta_1}B^{\eta_1+1} + A_{12}^{COAL}P^{-\eta_1}C^{1+\eta_1} + A_{21}^{COAL}C^{1+\eta_2}B^{-\eta_2}$ and $B_{11}^{COAL}P^{-\eta_1}B^{\eta_1+1} + B_{21}^{COAL}C^{1+\eta_2}B^{-\eta_2} + B_{22}^{COAL}C^{1+\eta_2}P^{-\eta_2}$, represents the possibility to fall into regime 3 and regime 1, respectively, or the possibility to switch off the power plant and get into regime 2 or 4. Table 1 summarizes the results just explained.

Section 3.3 discusses the signs of these constants and also provides the Net Present Value of the investment. Moreover, since Model 3 is the one that encompasses the other two models as special cases, each of the four possible regimes will be evaluated assuming different possible values for the power price, the price cap and the level of the cost. Finally, some sensitivity analyses will be discussed, to show how the value of the plant changes in relation to μ_B and σ_B in all four regimes.

4. Data and results

4.1. Empirical data and parameters estimation

In this section we calibrate the models using real market data.[18] In particular, the Italian wholesale single national power price - PUN (Prezzo Unico Nazionale - in Italian)[19] from 2009 to 2019 is taken as a proxy for the dynamics of P_t;

The price cap is estimated considering a gas-fired plant as the marginal technology. A full pass-through of cost into price is assumed.[20] Input cost are converted into energy ones depending on the technical efficiency of the plant η_i, $i = \{CCGT, COAL\}$. Moreover, it must be considered that power production from gas and coal includes emission costs $\xi(E^i)$ which depend on the technology-specific emission factor $emfac^i$ and the emission price $emprice$. Thus, price cap is estimated according to the following equation:

$$C_t = \frac{1}{\eta_{CCGT}} price^{GAS} + \xi(E^{CCGT}) \quad (50)$$

where

$$\xi(E^{CCGT}) = emfac^{CCGT} * emprice \quad (51)$$

where $emfac^{CCGT}$ is the emission factor of the considered gas-fired plants. For the COAL cost, they are estimated as:

$$B_t = \frac{1}{\eta_{COAL}} price^{COAL} + \xi(E^{COAL}) \quad (52)$$

where

$$\xi(E^{COAL}) = emfac^{COAL} * emprice \quad (53)$$

and $emfac^{COAL}$ is the emission factor of the considered coal-fired plants.

The figures of emission factors are based on the Italian average emissions from power plant, as provided by Caputo (2017). They amount to 0.365 tCO_2/MWh for gas, and 0.899 tCO_2/MWh for coal. Emissions are converted into money values by a carbon price, expressed in terms of money per unit of emission. There is a huge volatility of carbon price and a large interval of possible figures. A thorough discussion of the proper figure for a carbon price or a full evaluation of the models to calculate it goes beyond the scope of this paper.[21] We consider here a reference figure which derives from the estimate of the DICE model of Nordhaus (2017), that amounts to 33.87$ per ton of CO_2 for the year 2018.[22]

Finally, note that all figures expressed in terms of money per MWh are converted into money per MWy multiplying for the number of hours per year, and then discounted over an infinite horizon to obtain the values in terms of money per MW.

The price of gas ($price^{GAS}$) is estimated using the Natural Gas TTF Spot Price.[23] time series from 2008 to 2019. Coal price ($price^{COAL}$) is estimated using the COAL API2 Futures time series[24] from 2015 to 2019 for B_t. It is expressed in terms of $\$/t$ and converted into money per MWh using the standard conversion factor of 0.1228 tonne of coal equivalent per MWh. All three time series have been analyzed following

[18] The model time unit is the hour, except where differently stated. Unit measures are reported in Table 2.

[19] Source: GME - Gestore Mercati Energetici (https://www.mercatoelettrico.org).

[20] A full analysis of cost pass-through is beyond the scope of this paper. Nevertheless, here is some empirical evidence that in Italy there has been a consistent pass-through of input costs into electricity prices. See Caporin et al. (2021).

[21] For a concise review, see Zhang et al. (2021).

[22] Prices have been converted in euro using a 1.1 Euro–dollar conversion rate.

[23] Source: Eikon Refinitiv.

[24] Source: Investing (www.investing.com).

Table 1
Model 3 - regimes description.

Regime	Variables state	Plant state	V^{COAL}	Switching value
1st	$P \geq C > B$	Producing	Expected operating profits + Switching value	Possibility to fall in regime 3 or to switch off the power plant falling in regime 2 or 4
2nd	$B \geq C$ $(C-B) < (P-B)$	Idle	Switching value	Possibility to restart the production, falling in regime 1 or 3
3rd	$C > P > B$	Producing	Expected operating profits + Switching value	Possibility to fall in regime 1 or to switch off the power plant falling in regime 2 or 4
4th	$B \geq P$ $(P-B) < (C-B)$	Idle	Switching value	Possibility to restart the production falling in regime 1 or 3

the same procedure and considering monthly average prices.[25] First, we test whether the monthly averages of the three time series considered follow a Geometric Brownian Motion by adopting a Dickey–Fuller (DF) unit root test (see Appendix D). Then, we proceed by estimating the trend and uncertainty parameters, μ and σ.[26] We adopt $r = 5\%$ as the (yearly) risk-neutral discount factor (see Tan et al., 2020, Fu-Wei et al., 2022) and set $\alpha = 50\%$ in Model 2.

The value of the CRM (K) is assumed as 1,125,000 €/MW, which corresponds to the value of the CRM awarded to new capacity in the Italian Reliability Option auction held in 2019.[27]

For the investment costs figures, there can be a large variability. We assume the values presented in Bersani et al. (2022), using on-shore wind power as a reference for the VRE (1,750,000 €/MW, which correspond to 125,00 €/MWy). For the Long Duration Energy Storage of the VRE we assume a value of 2,500,000 €/MW (i.e., 87,500 €/MWy, source: Minkea and Tureka, 2018; Poli et al., 2021). While for gas and coal power plant we assume a value of 1,000,000 €/MW (i.e., 50,000 €/MWy) and 2,000,000 €/MW (i.e., 100,000 €/MWy), respectively (Bersani et al., 2022). Table 2 summarizes all values considered.

4.2. Results

The investment values and the switching values for all three models are reported in Table 3.

Note that the values of P_0, C_0 and B_0 imply that we are in regime 2 for VRE and CCGT and in regime 3 for COAL. The deterministic component of the value functions V^i, described in Eq. (7) for VRE and Eq. (18) for the CCGT, amount to 8,987,969 and to 4,317,337 €/MW, respectively. Thus, Table 3 shows that the switching values for both CCGT and VRE are negative, i.e., the possibility to fall into the other regimes and have the price capped by the CRM and/or being idle reduces the values.

The value functions for the three technologies are such that the value for COAL is the highest, followed by VRE and CCGT. However, this must be coupled with the remuneration accruing from the CRM, on the one hand, and the investment costs on the other hand, that yield the investment's values. The high investment cost of VRE more than compensate the slight advantage in terms of operating value, when compared to CCGT. The same is true for COAL, compared to CCGT. This induces a ranking of investment's value such that CCGT plants have the highest investment values, followed by COAL and then renewables. This is a ranking that is not desirable from an energy transition perspective. Even if gas-fired plants have higher investment values compared to coal-fired ones, both carbon emitting technologies are preferred from an economic point of view, while renewable, that do not emit, cannot even recover their investment costs. Clearly, this result is driven, *ceteris paribus*, by the high investment costs of VRE. Nevertheless, even if we remove the extra investment cost due to storage for renewables (recall that we have assumed a figure of 125,000 €/MWy i.e. 2,5000,000 €/MW for the investment in Long Duration Energy Storage capability that would enable the VRE to provide firm capacity to the capacity market) we obtain a figure that, albeit slightly positive, would not be enough to invert the ranking of the investments.

5. Sensitivity analyses

Model 1: VRE

Starting from the analytical solution in Section 4.1, we are first interested in the sensitivity of the two constants A^{VRE} and B^{VRE} to changes in the drift parameters for both P and C. Note that we constraint acceptable values for μ_P and μ_C such that $r - \mu_P > 0$ and $r - \mu_C > 0$, in order to obtain meaningful solutions for Eq. (8) of A^{VRE} and (9) of B^{VRE}. Consequently, we constraint the range of μ_P and μ_C to $[-0.2, 0.045]$. This will be maintained for all analyses unless differently stated.

As expected, both constants show negative values as the drifts change. It means that in both regime 1 and regime 2 the present value of the operating profits, V^{VRE}, decrease because of the CRM. As said before, the reason is that with a CRM electricity prices are capped, and this is a constraint on the expected flow of revenues. Note that B falls as μ_P rises, while it remains roughly unchanged in relation to variations of μ_C. This is as expected, given that falling into regime 1 from regime 2 implies losing the possibility of having extra revenues accruing from P, because of the price cap effect. Similarly, A falls as μ_C rises since it increases the possibility of falling into regime 2, in which revenues are capped.

Let us consider now how the value V^{VRE} changes depending on the drift and the volatility parameters of both the day ahead electricity prices and the marginal cost of the marginal technology. For brevity we reported here for Model 1 and 2 just the representation of V^{VRE} in regime 1 where $P < C$.

Both plots in Fig. 5 are based on the analytical Eq. (7). The graph on the left hand side displays V_1^{VRE} as a function of the drift terms μ_P and μ_C. In this case, the Value function V^{VRE} is a convex curve and it is positive correlated with the both drift terms. This implies that the expected present value of the operating profits accruing from the price (eventually capped) more than compensates the negative switching effect as the price and the cap rises, and this explains the behavior of the value function. The graph on the right hand side show how V^{VRE} changes in relation to the variation of volatility terms σ_C and σ_P.

[25] Monthly averages are retrieved from hourly prices. The sample is limited to the end of 2019, excluding the COVID-19 period and the price turmoils due to the Ukrainian war contingencies.

[26] Let us define $a_{Y,t} = ln(\frac{Y_t}{Y_{t-1}})$ *with* $\{Y = P, C, B\}$, the monthly log-returns of the three variables considered. We can estimate the volatility term as $\sigma_Y = \sqrt{Var(a_{Y,t})}$. The drift term, μ_Y, of PUN and API2 was estimated by adopting the following relation $\mu_Y = \overline{a_{Y,t}} + \frac{\sigma_Y^2}{2}$ *with* $\{Y = P, B\}$ and where $\overline{a_{Y,t}}$ is the monthly log-returns mean. The drift term of Natural Gas was estimated by adopting the linear regression $log(C_t) = c + \mu_C t + \epsilon_t$. The different procedure adopted derive from the need to provide the best possible estimate, on the basis of the available data.

[27] 75.000 for 15 years.

Table 2
Description of parameters and their sources.

Meaning	Symbols	Value	Unit of measure	Source
Risk-free inter. rate	r	5.00	%	Tan et al. (2020), Fu-Wei et al. (2022)
Capacity remuneration	K	75.00	k€/MWy	Resolution 399/2021/R/eel[a]
Investment cost in renewables	I^{VRE}	4.25	M€/MW	Minkea and Tureka (2018), Poli et al. (2021)
Investment cost in CCGT plants	I^{CCGT}	1.00	M€/MW	Bersani et al. (2022)
Investment cost in coal-fired plants	I^{COAL}	2.00	M€/MW	Bersani et al. (2022)
Emission factor of CCGT	$emfac^{CCGT}$	0.36	tCO_2/MWh	Caputo (2017)
Emission factor of COAL	$emfac^{COAL}$	0.89	tCO_2/MWh	Caputo (2017)
Emission price	$emprice$	30.79	€/tCO_2	Nordhaus (2017)
Technical efficiency of CCGT	η_{CCGT}	40.00	%	Zero Emissions Platform (ZEP) (2013)
Technical efficiency of COAL	η_{COAL}	40.00	%	Zero Emissions Platform (ZEP) (2013)
Price of Gas	$price^{GAS}$	19.39	€/MWh	Estimated from TTF Spot Price data
Price of Coal	$price^{COAL}$	8.71	€/MWh	Estimated from API2 Futures data
Power price	P_0	59.21	€/MWh	Estimated from PUN data
Price cap induced by the CRM	C_0	59.70	€/MWh	Computed
Input cost for coal	B_0	49.47	€/MWh	Computed
Drift rate of power price	μ_P	−0.77	%	Computed
Drift rate of price cap	μ_C	−0.59	%	Computed
Drift rate of coal input cost	μ_B	00.96	%	Computed
Volatility rate of power price	σ_P	37.37	%	Computed
Volatility rate of price cap	σ_C	36.75	%	Computed
Volatility rate of coal input cost	σ_B	24.53	%	Computed
Capacity factor of VRE	$capfac^{VRE}$	29.00	%	International Energy Agency (IEA) (2021)
Capacity factor of CCGT	$capfac^{CCGT}$	50.00	%	International Energy Agency (IEA) (2021)
Capacity factor of Coal	$capfac^{COAL}$	25.00	%	International Energy Agency (IEA) (2021)
Root of Eq. (10)	β_1	0.18	–	Computed
Root of Eq. (11)	β_2	−1.19	–	Computed
Root of Eq. (44)	η_1	1.0.5	–	Computed
Root of Eq. (45)	η_2	−2.16	–	Computed
Drift rate of $\frac{P}{B}$	μ_p	1.27	%	Computed
Drift rate of $\frac{C}{B}$	μ_c	1.44	%	Computed
Volatility rate of $\frac{P}{B}$	σ_p	12.84	%	Computed
Volatility rate of $\frac{C}{B}$	σ_c	12.22	%	Computed

[a] Resolution of Italian Regulatory Authority for Energy, Networks and Environment (ARERA) available at https://www.arera.it/fileadmin/allegati/docs/21/399-21.pdf.

Table 3
Investment values in VRE, CCGT and COAL fired plants. All figures are in €/MW.

	VRE	CCGT	COAL
V^i	1,026,327	605,503	943,406
K	1,125,000	1,125,000	1,125,000
I^i	4,250,000	1,000,000	2,000,000
Π^i	−2,302,430	855,503	193,406

In this case, V^{VRE} is a concave function and it is negative correlated with both volatility terms. It means that the investment value decreases when the uncertainty about the two underlings (the electricity price and the price cap opportunity cost) increases. Indeed, the value of the function V_1^{VRE} in Eq. (7) depends on the term A^{VRE} in Eq. (8), which represents the value of the possibility that once the plant, being in the regime $P > C$, falls into the other one (i.e., $P < C$). Its sign is given by the fraction $\frac{(r-\mu_C)+\beta_2(\mu_P-\mu_C)}{(\beta_2-\beta_1)(r-\mu_P)(r-\mu_C)}$. The denominator is always negative since $(\beta_2 - \beta_1) < 0$. The numerator can be positive or negative since it depends on the sign of the term $\beta_2(\mu_P - \mu_C)$, where $\beta_2 < 0$. Depending on the data describing the process of P and C, the switching from one state to the other could add or subtract value to the project. In the case displayed in Fig. 5, we have $\mu_P - \mu_C = -0.771 - (-0.599) = -0.172.$, so the numerator is positive and $A^{VRE} < 0$. Thus, in this case, a rise of uncertainty reduces the value of the investment, due to the existence of C that caps the revenues.

Model 2: CCGT

In this section, looking at the analytical Equations of Model 2 given by (20), (21), (22) and (23) in Section 4.2, we first evaluate the sensitivity of the four constants to $r - \mu_P$ and $r - \mu_C$. Note that, differently from Model 1, there is an additional parameter α. The results are presented in Fig. 6. As expected, constants A_1^{CCGT} and B_2^{CCGT} are negative while A_2^{CCGT} and B_3^{CCGT} are positive. In particular, B_3^{CCGT} represents the value of the possibility to restart selling power when the plant is in regime 3. Since in this regime the plant is not earning revenues, the possibility to restart production has clearly a positive impact on the value. Note that it rises as μ_P and μ_C increase ($r - \mu_P$ and $r - \mu_C$ reduces). A_2^{CCGT} captures the possibility to fall into regime 1 when the plant is in regime 2. Also in this case, the value is positive since in the first regime there is no price cap effect, while it affects revenues in regime 2. A similar rationale to the case before explains why A_1^{CCGT} is negative, since it depends on the possibility to fall into regime 2 when the plant is in regime 1. For both A_1^{CCGT} and A_2^{CCGT} the value rises as μ_C increases, and they are hardly sensitive to change of the drift of P. Finally, B_2^{CCGT} represent the opportunity to fall into regime 3 in which the plant is idle and it does not earn revenues, which implies that the corresponding switching value is negative. It decreases

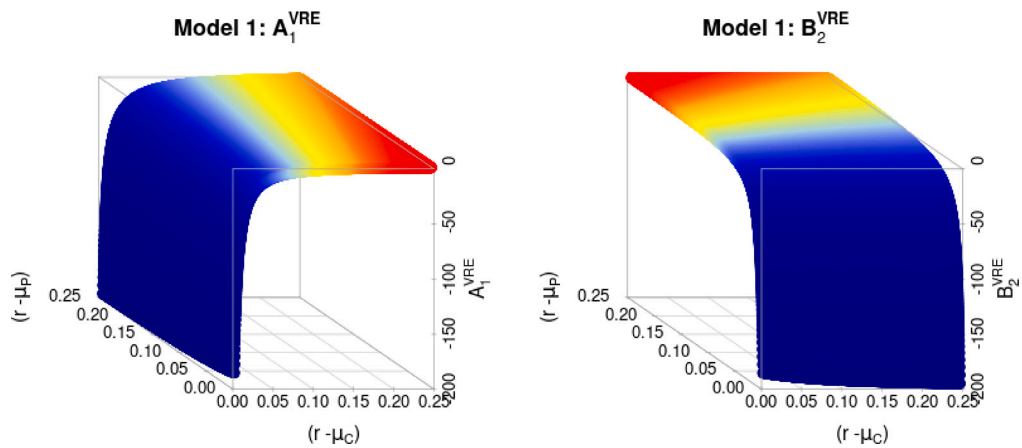

Fig. 4. Sensitivity analysis of A^{VRE} and B^{VRE} with respect to variations in $(r - \mu_P)$ and $(r - \mu_C)$.

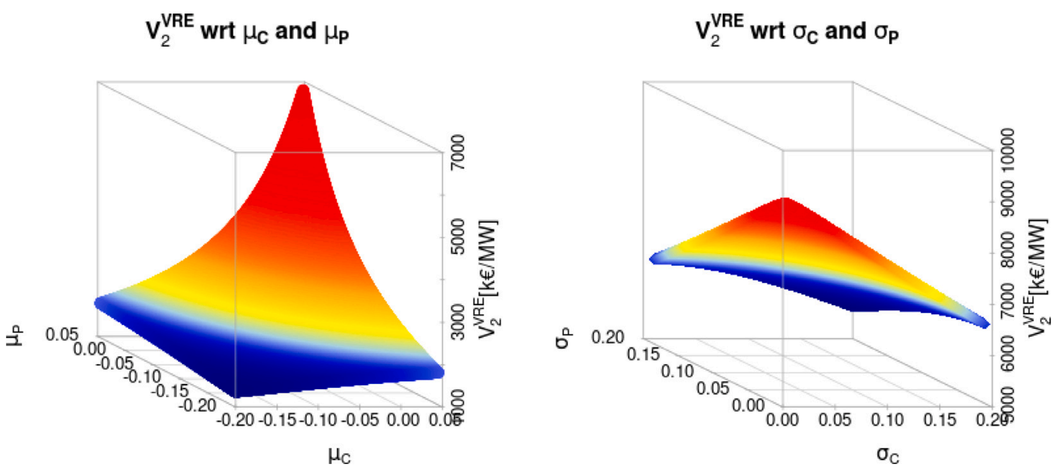

Fig. 5. Sensitivity analysis of V_2^{VRE} with respect to variations in μ_P and μ_C (left) and σ_P and σ_C (right).

as μ_P rises, and it is hardly sensitive to changes in μ_C, a behavior that is meaningful taking into account that in regime 2 revenues are determined by P (which is below C) and are lost when going into regime 3. Comparing the value of the constants with those of Model 1, we see that the constant A^{VRE} shows a level twice as high as the constant A_1^{CCGT}; this is due to the presence of the own generation costs that shrink its value. The constant B_2^{CCGT} is instead identical to B^{VRE} of Fig. 4. Indeed, their equations are exactly the same. Finally, it should be noted that the absolute value of the constant B_3^{CCGT} is approximately more than ten times smaller than that of the other three constants.

Let us focus now on the sensitivity of V^{CCGT} to μ_P and μ_C, and to σ_P and μ_C, respectively. The plots displayed in Fig. 7, that are based on the analytical Eq. (17), are similar to the ones in Fig. 5. The main difference is that now the value is lower; this is due to the fact that in this model there are generation costs that decrease the firm operating profits.

Model 3 - COAL

In this section we show who the constants of Eq. (33) change as the drift parameters for both P and C varies. Note that, for simplicity we just focus on the constant for Regime 3, that is, the regime that arises given the calibration shown in the previous section. We see that the constant are reduced monotonically by the increase in the drift of one of the parameters (the electricity price for B_{11} and B_{22} and the price cap for B_{21}), being roughly constant with respect to the other, similarly to what happens for the VRE and CCGT models (see Fig. 8).

Finally, we show how the value function changes, depending on the drift and the volatility of P and C. As before, we focus on the third regime. We see that the reduction of the drifts lowers the value function, as it is obvious since it implies less expected prices and a more tight price cap i.e., less revenues. On the contrary, we observe a decreasing yet non linear impact of the volatility on the value, due to the complex impact that volatility has on each of the constants of the value function (see Fig. 9).

Sensitivity with respect to emissions cost

In this section, we calculate how the investment values change for different possible values of the emission cost. We are well aware that it is extremely difficult estimating a proper value for the emission cost, and that moreover it might be random. Including uncertainty about future evolution of the emission cost would make the model analytically unsolvable, and is beyond the scope of this paper. What we show here is how much the investment values are affected assuming that different figure for it are observed at the time of the investment and that the investor regards them as reliable enough to treat them as constant. Recall that the emission cost enters into the figures of the price cap and the input cost for the CCGT and COAL model, through Eqs. (50) and (52). Therefore, from an analytical point of view, the analysis we show here is equivalent to assume that different starting values for the variables C_0 and B_0 are observed. Pictures 10 and 11 show how the value functions V^i change for different levels of $emprice$.

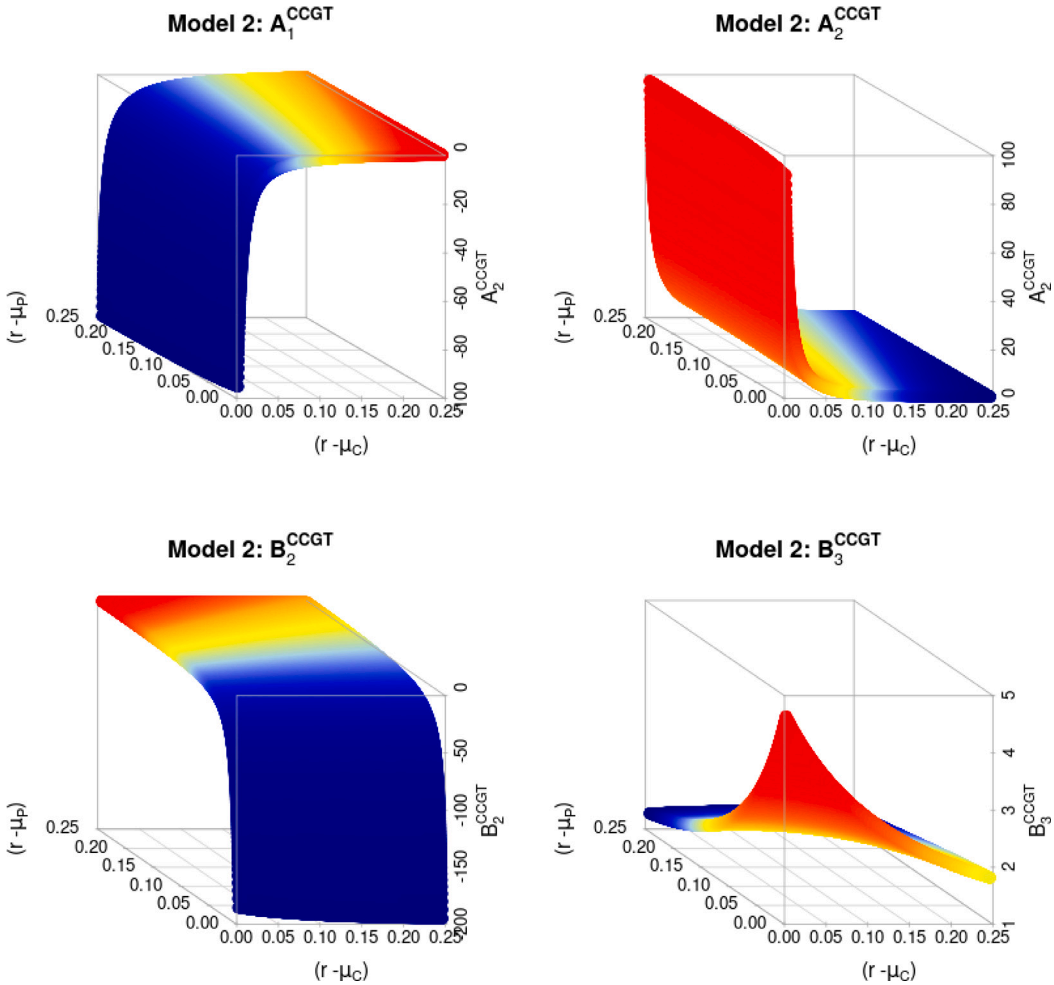

Fig. 6. Sensitivity analysis of A_1^{CCGT}, A_2^{CCGT}, B_2^{CCGT} and B_3^{CCGT} with respect to variations in $(r - \mu_P)$ and $(r - \mu_C)$.

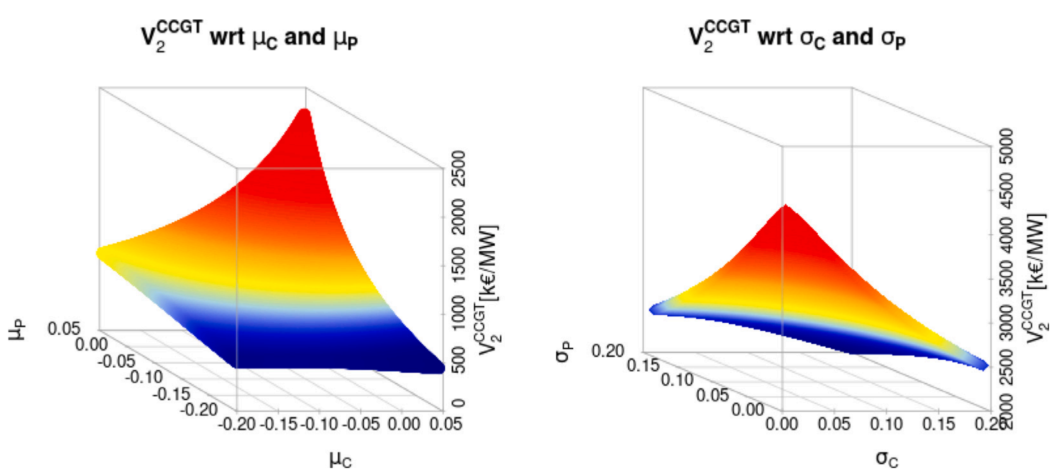

Fig. 7. Sensitivity analysis of V_2^{CCGT} with respect to variations in μ_P and μ_C (left) and σ_P and σ_C (right).

Let us start with Fig. 10. As the emission price (*emprice*) changes, different regimes apply. When the emission cost is null, the value V^{CCGT} is in regime 1. As the emission price rises, V^{CCGT} moves into regime 2, where the price cap becomes non-binding. Eventually, V^{CCGT} enters regime 3 when the emission cost is so high that the plant ceases production. The investment value increases with the emission price due to a reduction in the impact of the price cap, which rises with the increase in emission price. This effect outweighs the rise in own cost. However, in regime 2, the potential shift to regime 3, coupled with the rising own costs, induces a non-linear effect on investment values, causing them to eventually decrease. This reduction is further exacerbated in regime 3, where the own costs are so high that the plant stops producing.

Fig. 11 presents a different pattern. Initially, the value V^{COAL} decreases and then increases. When the emission prices are very low, the value derives from regime 1, characterized by a binding price

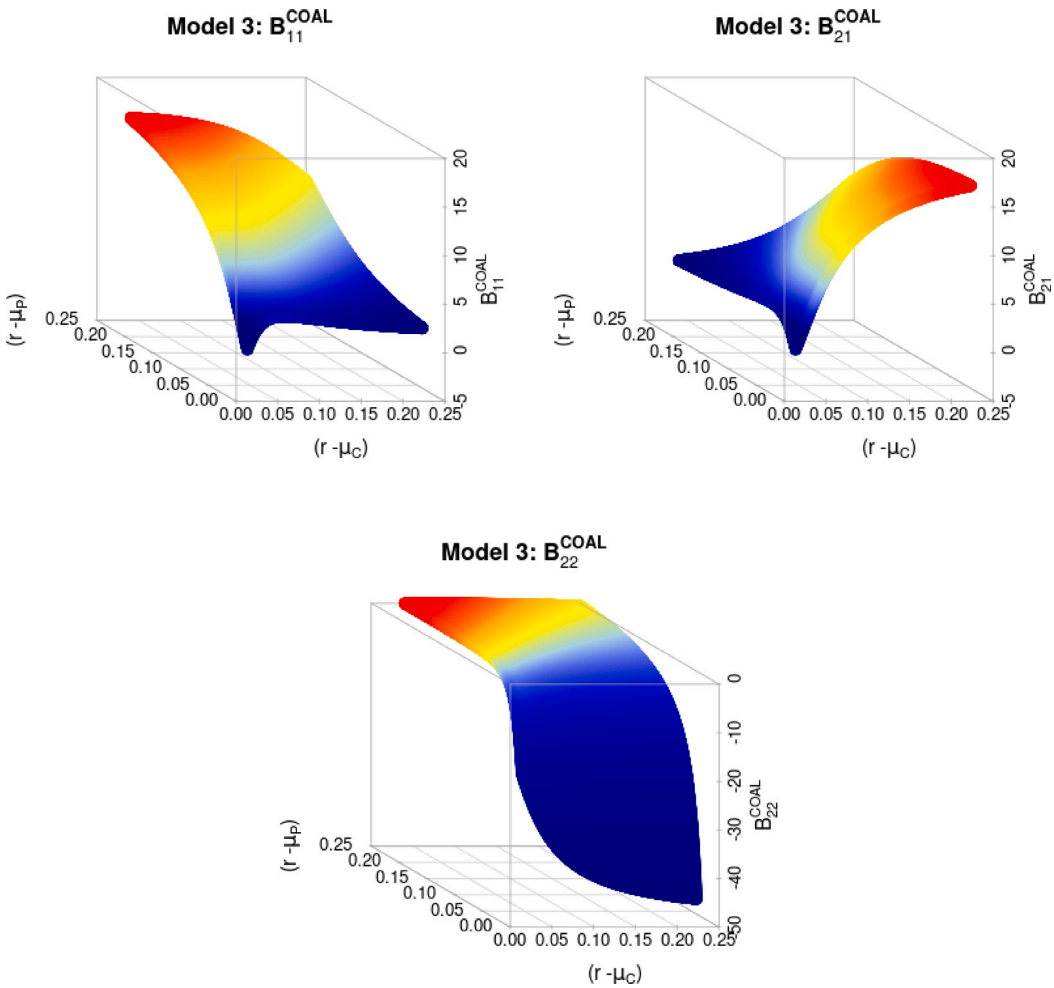

Fig. 8. Sensitivity analysis of B_{11}^{COAL}, B_{21}^{COAL} and B_{21}^{COAL} with respect to variations in $(r - \mu_P)$ and $(r - \mu_C)$.

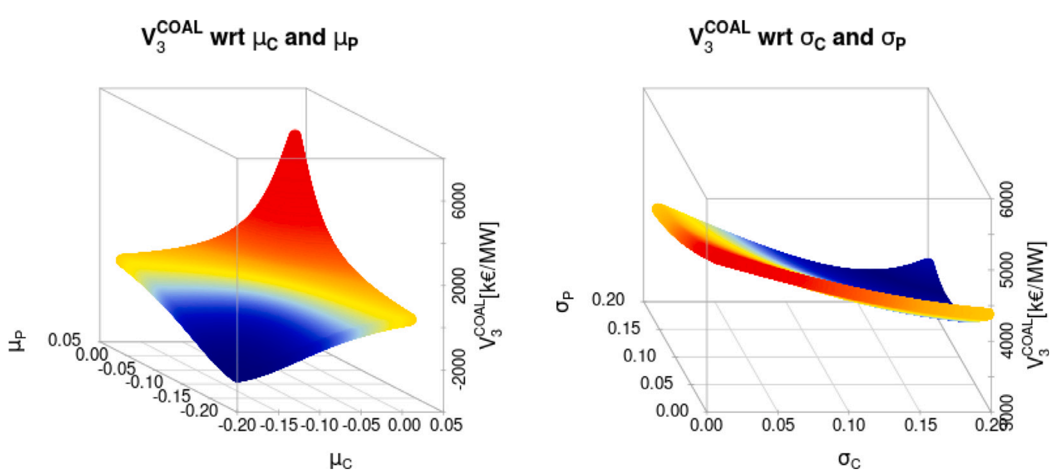

Fig. 9. Sensitivity analysis of V_3^{COAL} with respect to variations in μ_P and μ_C (left) and σ_P and σ_C (right).

cap. As the emission prices rise, both the price cap and own costs increase, lowering the investment value as it moves into Regime 3. In this scenario, even if the price cap becomes non-binding, the value is diminished by the increase in own costs and the possibility of entering regime 4, where the plant is idle due to too-high own cost. As the emission costs continue to rise, V^{COAL} moves into regime 4. Here, the investment value becomes an option value since the plant is idle and the value stems solely from the potential to restart production.

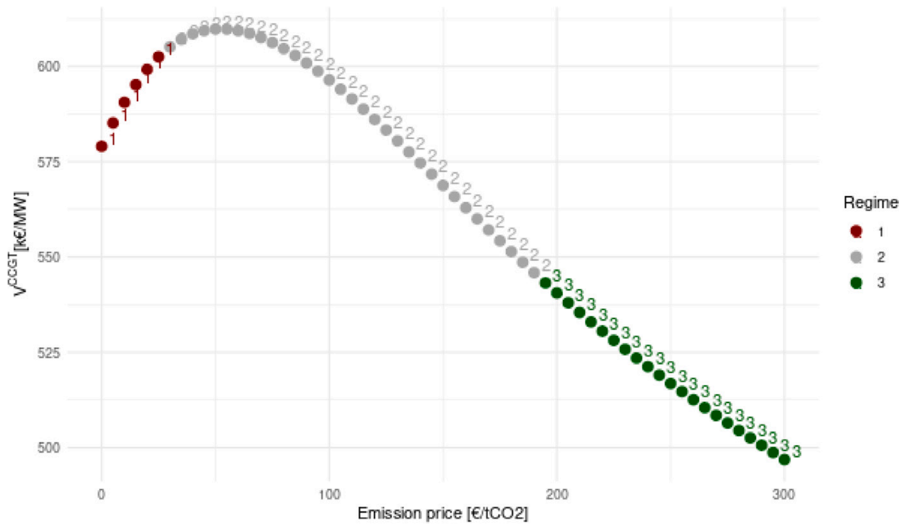

Fig. 10. The value function V^{CCGT} for different levels of *emprice*.

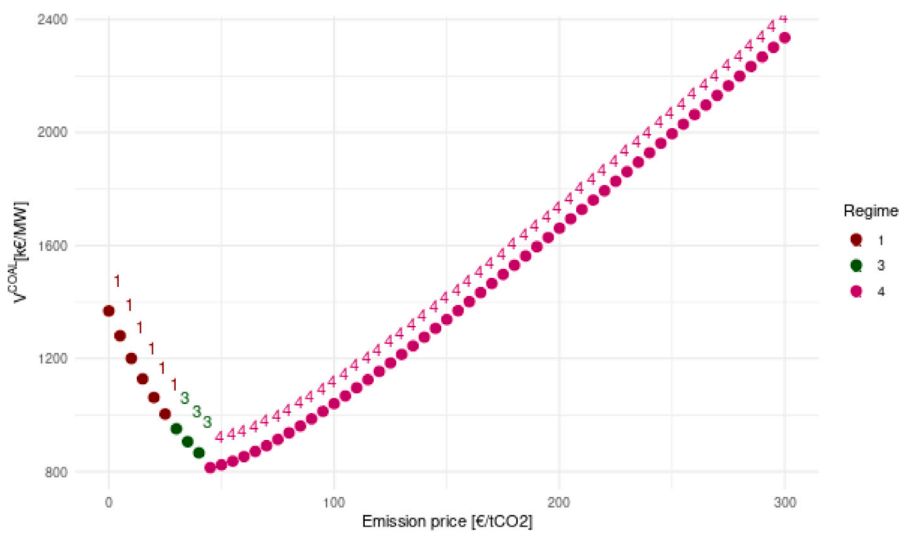

Fig. 11. The value function V^{COAL} for different levels of *emprice*.

6. Conclusions

The aim of this paper was to investigate the value of investments in capacity financed by a Capacity Remuneration Mechanism, by adopting a stochastic approach. In electricity market, producers can be paid with a CRM based on both the availability to generate electricity as well as the electricity produced. Thus, the Net Present Value of a technology under a CRM is determined by its investment costs, a capacity premium and its Value function.

In order to distinguish between capacity that supports energy transition and capacity that hinders technological evolution, we developed three analytical models to study the value of three different technologies: capacity provided by Variable Renewable Energy source coupled with Long Duration Energy Storage device enabling firm capacity (Model 1); thermally efficient capacity more efficient than the marginal power plant at the time of investment (Model 2); and brown capacity (Model 3). These technologies have different expected operating profits and are influenced by different underlying stochastic variables, including electricity prices, the marginal cost of the marginal technology, and generation costs. The three analytical models developed vary in complexity, from the simplest VRE technology model with two underlying stochastic variables (electricity prices and marginal cost of the marginal technology) to the most complex model with three stochastic variables (electricity prices, marginal cost of the marginal technology, and generation costs). For all three models, the value function consists of different regimes depending on the level of the variables considered.

We estimate the value of the investment using plausible data derived from Italian prices. Our choice is motivated from the need to provide data derived form a market where a CRM is in place.[28] However, we emphasize that the models can be applied to any market provided that proper estimates are calculated. We show the ranking of the values of the investments across the three considered technologies and compare it with the ranking given by their emissions. We find that the investment values ranking is not aligned with the need for energy transition, which calls for an increase in carbon-free power generation. Interestingly enough, this is not due to the investment cost of carbon-fired plants: a change in the investment costs of Coal compared to CCGT

[28] Terna – the Italian TSO – run two capacity auctions in November 2019 and in February 2022, for the delivery in 2023 and 2024.
https://www.terna.it/it/sistema-elettrico/pubblicazioni/news-operatori/dettaglio/esiti-asta-madre-2022-mercato-della-capacita,
https://www.terna.it/en/electric-system/publications/operators-news/detail/capacity-market-results-main-auction-2024.

would only have the effect of a change in the relative value of the two technologies, but would not induce a change in the merit order of the investment in VRE perspective. Moreover, a rise in carbon emission prices would not be decisive either, as it would lower the investment value of CCGT but increase the value of investment in Coal-fired plants, even if kept idle, due to a spike in the option value of restarting production should prices rise. The decisive variable to make renewable competitive in providing firm capacity would be lowering their cost of investment, in particular in the LDES component. This is particularly relevant form a policy perspective and should be taken into account when comparing the need of providing security of supply through the introduction of CRM with the energy transition perspectives.

CRediT authorship contribution statement

Cinzia Bonaldo: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Fulvio Fontini:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Michele Moretto:** Writing – review & editing, Writing – original draft, Validation, Supervision, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

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Appendix A. Proof of Proposition 1

Starting from Eq. (6), a standard stochastic dynamic programming methods was adopted to obtain a close form solution for the value function $V^{VRE}(P,C)$ distinguishing the case in which $P \geq C$ or $P < C$.

For simplicity, let us refer to V_2^{VRE} as V^2, i.e., the value of the investment in the region where $P < C$, it must satisfy the following Bellman equation:

$$rV^2(P,C) = P + \frac{\mathbb{E}_t(dV^2(P,C))}{dt}, \text{ for } P < C \tag{A.1}$$

Over a time interval dt, the total expected return on the investment opportunity, $rV^2(P,C)dt$, is equal to its expected rate of capital appreciation. Using Ito's Lemma the above no arbitrage condition can be written as the Bellman equation:

$$rV^2(P,C) = P + \mu_P P V_P^2 + \frac{1}{2}\sigma_P^2 P^2 V_{PP}^2 + \mu_C C V_C^2 + \frac{1}{2}\sigma_C^2 C^2 V_{CC}^2 \tag{A.2}$$

where V_P^2, V_{PP}^2, V_C^2 and V_{CC}^2 are the first and second derivatives of $V^2(P,C)$ with respect to P and C respectively. Eq. (A.2) captures the relationship between the two stochastic variables, P and C. Since the market value represents an homogeneous structure we are able to write the objective function $V^2(P,C)$ as a function of the ratio $x = \frac{C}{P}$ and write $V^2(P,C) = Cv^2(x)$. Using the definition of x, we convert the partial differential Eq. (A.2) as:

$$\begin{aligned} rCv^2(x) =& P + -\mu_P P x^2 v_x^2(x) + \frac{1}{2}\sigma_P^2 P^2 (2x^2 \frac{1}{P} v_x^2(x) + x^3 v_{xx}^2(x)(\frac{1}{P})) \\ &+ \mu_C C(v^2(x) + x v_x^2(x)) + \frac{1}{2}\sigma_C^2 C^2 (\frac{2}{P} v_x^2(x) + x v_{xx}^2(x)\frac{1}{P}) \end{aligned} \tag{A.3}$$

$$\begin{aligned} (r-\mu_C)Cv^2(x) =& P + v_x^2(x)((\sigma_P^2 - \mu_P)Px^2 + (\mu_C + \sigma_C^2)Cx) \\ &+ \frac{1}{2}\sigma_P^2 P x^3 v_{xx}^2(x) + \frac{1}{2}\sigma_C^2 C x^2 v_{xx}^2(x) \end{aligned} \tag{A.4}$$

where:

$$\begin{aligned} V_P^2 &= Cv_x^2(x)\left(-\frac{C}{P^2}\right) = -x^2 v_x^2(x) \\ V_C^2 &= v^2(x) + Cv_x^2(x)\frac{1}{P} = v^2(x) + x v_x^2(x) \\ V_{PP}^2 &= 2x^2\frac{1}{P}v_x^2(x) + x^3 v_{xx}^2(x)\left(\frac{1}{P}\right) \\ V_{CC}^2 &= \frac{2}{P}v_x^2(x) + x v_{xx}^2(x)\frac{1}{P} \end{aligned}$$

Let consider the homogeneous part of (A.4). Dividing both parts by C we obtain an ordinary differential equation for the unknown function $v^2(x)$:

$$(r-\mu_C)v^2(x) = (\mu_C - \mu_P + \sigma_C^2 + \sigma_P^2)x v_x^2(x) + \frac{1}{2}(\sigma_C^2 + \sigma_P^2)x^2 v_{xx}^2(x) \tag{A.5}$$

A general solution for (A.5) is:

$$v^2(x) = A_2 x^{\beta_1} + B_2 x^{\beta_2} \tag{A.6}$$

where:

$$\beta_1 = -\left(\frac{1}{2} + \frac{\mu_C - \mu_P}{\sigma_C^2 + \sigma_P^2}\right) + \sqrt{\left(\frac{1}{2} + \frac{\mu_C - \mu_P}{\sigma_C^2 + \sigma_P^2}\right)^2 + \frac{2(r-\mu_C)}{\sigma_C^2 + \sigma_P^2}} > 0$$

$$\beta_2 = -\left(\frac{1}{2} + \frac{\mu_C - \mu_P}{\sigma_C^2 + \sigma_P^2}\right) - \sqrt{\left(\frac{1}{2} + \frac{\mu_C - \mu_P}{\sigma_C^2 + \sigma_P^2}\right)^2 + \frac{2(r-\mu_C)}{\sigma_C^2 + \sigma_P^2}} < 0$$

are the positive and negative roots of the fundamental quadratic equation:

$$\frac{1}{2}(\sigma_C^2 + \sigma_P^2)\beta^2 + (\mu_C - \mu_P + \frac{1}{2}(\sigma_C^2 + \sigma_P^2))\beta - (r - \mu_C) = 0 \tag{A.7}$$

Adding a linear particular solution for (A.5), the value function $V^2(P,C)$ can thus be expressed as:

$$V^2(P,C) = \frac{P}{r-\mu_P} + CA_2 x^{\beta_1} + CB_2 x^{\beta_2} \quad \text{for } P < C \tag{A.8}$$

See that the terms $CA_2x^{\beta_1} + CB_2x^{\beta_2}$, capture the value of the possibility of entering into the second regime, i.e., of having the price cap effect binding. Following the standard procedure, we impose proper boundary conditions to rule out some implausible solutions. The first boundary condition for the valuation PDE is given when $x \to \infty$, that is to say, either the electricity day-ahead price tends to zero or price cap tends to infinite. In this case there is no possibility of having the price cap effect binding. Thus, the value of being into that regime vanishes. In other words, when $\lim_{x\to\infty} V^2(P,C) = \frac{P}{r-\mu_P}$. Thus, for the first regime $P < C$, we set $A_2 = 0$ and obtain:

$$\begin{aligned} V^2(P,C) &= \frac{P}{r-\mu_P} + CB_2 x^{\beta_2} \\ &= \frac{P}{r-\mu_P} + B_2 C^{1+\beta_2} P^{-\beta_2} \end{aligned} \tag{A.9}$$

Let us now indicate as $V^1(P,C)$ the value of the investment when the price cap effect is binding, i.e., when $P \geq C$,. It must satisfy the following Bellman equation:

$$rV^1(P,C) = C + \frac{\mathbb{E}_t(dV^1(P,C))}{dt} \quad P \geq C \tag{A.10}$$

Following the same rationale as before, the value function $V^1(P,C)$ can be expressed as:

$$V^1(P,C) = \frac{C}{r-\mu_C} + CA_1x^{\beta_1} + CB_1x^{\beta_2} \quad \text{for } P \geq C \tag{A.11}$$

The terms $CA_1x^{\beta_1} + CB_1x^{\beta_2}$ captures the value of entering into the second regime, i.e, having the price cap effect not binding. As before, we consider two boundary conditions. The first one is $x \to 0$, i.e., the electricity day-ahead price tends to infinite or the price cap effect to zero. In this case there is no possibility of entering into the other regime, thus its value vanishes. In other words, when $\lim_{x\to 0} V^1(P,C) = \frac{C}{r-\mu_C}$. This implies that when $P \geq C$ we can set $B_1 = 0$, i.e.:

$$\begin{aligned} V^1(P,C) &= \frac{C}{r-\mu_C} + CA_1x^{\beta_1} \\ &= \frac{C}{r-\mu_C} + A_1C^{1+\beta_1}P^{-\beta_1} \end{aligned} \tag{A.12}$$

Summing up, we get:

$$V(P,C) = \begin{cases} V^1(P,C) = \frac{C}{r-\mu_C} + A_1C^{1+\beta_1}P^{-\beta_1} & \text{for } P \geq C \\ V^2(P,C) = \frac{P}{r-\mu_P} + B_2C^{1+\beta_2}P^{-\beta_2} & \text{for } P < C \end{cases} \tag{A.13}$$

We aim to study the sign of the two switching values, and for this we calculate the explicit expressions of A_1 and B_2. In order to do so, we solve for the level of $x = 1$ which would make the investor indifferent from being into one regime ($P \geq C$) or the other ($P < C$). Such a level is $\frac{C}{P} = 1$, which allows determining the constants A_1^{VRE} and B_2^{VRE} by imposing the Matching Value (MV) and the Smooth Pasting (SP) conditions:

$$\begin{aligned} \frac{P}{r-\mu_P} + B_2C^{1+\beta_2}P^{-\beta_2} &= \frac{C}{r-\mu_C} + A_1C^{1+\beta_1}P^{-\beta_1} && \text{MV} \\ \frac{1}{r-\mu_P} - \beta_2B_2C^{1+\beta_2}P^{-\beta_2-1} &= -\beta_1A_1C^{1+\beta_1}P^{-\beta_1-1} && \text{SP w.r.t. } P \\ (1+\beta_2)B_2C^{\beta_2}P^{-\beta_2} &= \frac{1}{r-\mu_C} + (1+\beta_1)A_1C^{\beta_1}P^{-\beta_1} && \text{SP w.r.t. } C \end{aligned}$$

Solving the system we obtain:

$$A_1 = \frac{(r-\mu_C) + \beta_2(\mu_P - \mu_C)}{(\beta_2-\beta_1)(r-\mu_P)(r-\mu_C)} \tag{A.14}$$

$$B_2 = \frac{(\mu_P-\mu_C)\beta_1 + (r-\mu_C)}{(\beta_2-\beta_1)(r-\mu_P)(r-\mu_C)} \tag{A.15}$$

Finally, defining $A_1 = A^{VRE}$, and $B_2 = B^{VRE}$ we get the expression in the text.

Appendix B. Proof of Proposition 2

Starting from Eq. (15), a similar procedure as in "Proof of Proposition 1" was followed.

$$V^{CCGT}(P,C) = \begin{cases} V_1^{CCGT}(P,C) = \frac{(1-\alpha)C}{r-\mu_C} + A_1C^{1+\beta_1}P^{-\beta_1} \text{ for } P_t \geq C_t \\ V_2^{CCGT}(P,C) = \frac{P}{r-\mu_P} - \frac{\alpha C}{r-\mu_C} + A_2C^{1+\beta_1}P^{-\beta_1} + B_2C^{1+\beta_2}P^{-\beta_2} \\ \qquad \text{for } \alpha C_t < P_t < C_t \\ V_3^{CCGT}(P,C) = B_3C^{1+\beta_2}P^{-\beta_2} \quad \text{for } P_t < \alpha C_t \end{cases} \tag{B.1}$$

The constants A_1, A_2, B_2, and B_3 are determined by imposing the matching condition and the smooth pasting condition. We start by computing the Matching Value (MV) and the Smooth Pasting (SP) conditions between first and second regime in $\frac{C}{P} = 1$.

$$\begin{aligned} \frac{(1-\alpha)C}{r-\mu_C} + A_1C^{1+\beta_1}P^{-\beta_1} &= \frac{P}{r-\mu_P} - \frac{\alpha C}{r-\mu_C} + A_2C^{1+\beta_1}P^{-\beta_1} \\ &\quad + B_2C^{1+\beta_2}P^{-\beta_2} && \text{MV} \\ \frac{(1-\alpha)}{r-\mu_C} + A_1(1+\beta_1)C^{\beta_1}P^{-\beta_1} &= -\frac{\alpha}{r-\mu_C} + A_2(1+\beta_1)C^{\beta_1}P^{-\beta_1} \\ &\quad + B_2(1+\beta_2)C^{\beta_2}P^{-\beta_2} && \text{SP w.t. } C \\ -A_1\beta_1C^{1+\beta_1}P^{-\beta_1-1} &= \frac{1}{r-\mu_P} - A_2\beta_1C^{1+\beta_1}P^{-\beta_1-1} \\ &\quad - B_2\beta_2C^{1+\beta_2}P^{-\beta_2-1} && \text{SP w.t. } P \end{aligned}$$

After some algebraic steps we get:

$$\begin{aligned} \frac{1}{r-\mu_C} + A_1 &= \frac{1}{r-\mu_P} + A_2 + B_2 \\ \frac{1}{r-\mu_C} + A_1(1+\beta_1) &= A_2(1+\beta_1) + B_2(1+\beta_2) \\ -A_1\beta_1 &= \frac{1}{r-\mu_P} - A_2\beta_1 - B_2\beta_2 \end{aligned}$$

Then we compute the Matching Value (MV) and the Smooth Pasting (SP) conditions between the first and the third regime in $\frac{C}{P} = \frac{1}{\alpha}$.

$$\begin{aligned} \frac{P}{r-\mu_P} - \frac{\alpha C}{r-\mu_C} + A_2C^{1+\beta_1}P^{-\beta_1} + B_2C^{1+\beta_2}P^{-\beta_2} &= B_3C^{1+\beta_2}P^{-\beta_2} && \text{MV} \\ -\frac{\alpha}{r-\mu_C} + A_2(1+\beta_1)x^{\beta_1} + B_2(1+\beta_2)x^{\beta_2} &= B_3(1+\beta_2)C^{\beta_2}P^{-\beta_2} && \text{SPC w..t. } C \\ \frac{1}{r-\mu_P} - A_2\beta_1x^{1+\beta_1} - B_2\beta_2x^{1+\beta_2} &= -B_3\beta_2C^{1+\beta_2}P^{-\beta_2-1} && \text{SP w.t. } P \end{aligned}$$

After some algebraic steps we get:

$$\begin{aligned} \frac{\alpha}{r-\mu_P} - \frac{\alpha}{r-\mu_C} + A_2\alpha^{-\beta_1} + B_2\alpha^{-\beta_2} &= B_3\alpha^{-\beta_2} \\ -\frac{\alpha}{r-\mu_C} + A_2(1+\beta_1)\alpha^{-\beta_1} + B_2(1+\beta_2)\alpha^{-\beta_2} &= B_3(1+\beta_2)\alpha^{-\beta_2} \\ \frac{1}{r-\mu_P} - A_2\beta_1\alpha^{-1-\beta_1} - B_2\beta_2\alpha^{-1-\beta_2} &= -B_3\beta_2\alpha^{-1-\beta_2} \end{aligned}$$

The system can be reduced to four equations in four unknown:

$$\begin{aligned} -A_2 - B_2 + A_1 &= \frac{1}{r-\mu_P} - \frac{1}{r-\mu_C} \\ -A_2(1+\beta_1) - B_2(1+\beta_2) + A_1(1+\beta_1) &= -\frac{1}{r-\mu_C} \\ A_2\alpha^{-\beta_1} + (B_2 - B_3)\alpha^{-\beta_2} &= \frac{\alpha(\mu_C-\mu_P)}{(r-\mu_P)(r-\mu_C)} \\ A_2\alpha^{-\beta_1} + A_2\beta_1\alpha^{-\beta_1} + B_2\alpha^{-\beta_2} + B_2\beta_2\alpha^{-\beta_2} - B_3\alpha^{-\beta_2} - B_3\beta_2\alpha^{-\beta_2} &= \frac{\alpha}{r-\mu_C} \end{aligned}$$

Solving the system we obtain:

$$A_1 = \frac{(\mu_P-\mu_C)\beta_2 + (r-\mu_C)}{(\beta_2-\beta_1)(r-\mu_P)(r-\mu_C)}(1-\alpha^{\beta_1+1}) \tag{B.2}$$

$$A_2 = -\frac{\beta_2(\mu_P-\mu_C) + (r-\mu_C)}{(\beta_2-\beta_1)(r-\mu_P)(r-\mu_C)}\alpha^{\beta_1+1} \tag{B.3}$$

$$B_2 = \frac{(\mu_P-\mu_C)\beta_1 + (r-\mu_C)}{(\beta_2-\beta_1)(r-\mu_P)(r-\mu_C)} \tag{B.4}$$

$$B_3 = \frac{(\mu_P-\mu_C)\beta_1 + (r-\mu_C)}{(\beta_2-\beta_1)(r-\mu_P)(r-\mu_C)}(1-\alpha^{\beta_2+1}) \tag{B.5}$$

Finally defining $A_1^{CCGT} = A_1$, $A_2^{CCGT} = A_2$, $B_2^{CCGT} = B_2$ and $B_3^{CCGT} = B_3$ we get the expression in the text.

Appendix C. Proof of Proposition 3

Dividing (32) by B, the two-dimensional value of (32) is:

$$v(p,c) = E_0\left[\int_0^\infty \max[\min(p_t-1,\ c_t-1), 0]e^{-rt}dt\right] \tag{C.1}$$

where $p = \frac{P}{B}$ and $c = \frac{C}{B}$ are distributed as GBM:

$$\frac{dp}{p} = \mu_p dt + \sigma_p dW_t^p \quad \text{with } p_0 = p \tag{C.2}$$

$$\frac{dc}{c} = \mu_c dt + \sigma_c dW_t^c \quad \text{with } c_0 = c \tag{C.3}$$

and $\mu_p = \mu_P - \mu_B + \frac{1}{2}\sigma_B^2$, $\sigma_p = \sigma_P - \sigma_B$, $\mu_c = \mu_C - \mu_B + \frac{1}{2}\sigma_B^2$, $\sigma_c = \sigma_C - \sigma_B$.

As the presence of -1 in (C.1) plays the role of a running cost, the value $v(p,c)$ is given by a couple of optimal timing problem as:

$$v^{op,M3}(p,c) = \max_\tau E_0\left[\int_0^\tau \min(p_t-1,\ c_t-1)e^{-rt}dt + v^{nop,M3}(p_\tau, c_\tau)e^{-r\tau}\right] \tag{C.4}$$

$$v^{nop,M3}(p,c) = \max_{\tau} E_0\left[v^{op,M3}(p_\tau, c_\tau)e^{-r\tau}\right] \quad (C.5)$$

where the maximum is taken over stopping times as function of both p and c, that represents the times of switching from the regime of operation (i.e. $v^{op}(p,c)$), to the regime of inaction (i.e. $v^{nop}(p,c)$) and vice-versa. However, in contrast to the previous cases, the presence of running costs preclude the existence of close form solutions for both $v^{op}(p,c)$ and $v^{op}(p,c)$ and the optimal operating policy. That is, optimal operation provides for a period of inertia to cover the running costs (Detemple and Kitapbayev, 2020a,b).

Therefore, in order to obtain a close solution for (C.1), we proceed assuming, symmetrically with the previous cases, that the investor simply decides to stop producing when p and/or c go below 1, while it produces when both p and c are greater than one. This identifies 4 regimes: $p \geq c > 1$, $c > p > 1, p \leq 1$ and $c \leq 1$.

Let consider first the case when $p \geq c > 1$. Defining with $v^1(p,c)$, the value of the plant within this state is given by the solution of:

$$rv^1(p,c) = c-1+\mu_p p v^1_p+\frac{1}{2}\sigma_p^2 p^2 v^1_{pp}+\mu_c c v^1_c+\frac{1}{2}\sigma_c^2 c^2 v^1_{cc} \quad \text{for } p \geq c > 1 \quad (C.6)$$

Similarly, defining with $v^3(p,c)$ the value when $c > p > 1$, this is given by the solution of:

$$rv^3(p,c) = p-1+\mu_p p v^2_p+\frac{1}{2}\sigma_p^2 p^2 v^2_{pp}+\mu_c c v^2_c+\frac{1}{2}\sigma_c^2 c^2 v^2_{cc} \quad \text{for} \quad c > p > 1 \quad (C.7)$$

Considering now the regime in which the power plant is idle. If $p \geq c > 1$ this would happen for the first time when c goes below 1, so the power plant will be idle for all value of $p \in (0,\infty)$. That is, indicating with $v^2(p,c)$ the value of the plant is given by the solution of:

$$rv^2(p,c) = \mu_p p v^4_p+\frac{1}{2}\sigma_p^2 p^2 v^4_{pp}+\mu_c c v^4_c+\frac{1}{2}\sigma_c^2 c^2 v^4_{cc} \quad \text{for} \quad c \leq 1 \text{ for all } p \in (0,\infty) \quad (C.8)$$

In the same way, if $c > p > 1$, power plant stops production the first time that p goes below 1 and remains idle for all value assumed by $c \in (0,\infty)$. Indicating with $v^4(p,c)$ the value of the plant in this case, it is given by the solution of:

$$rv^4(p,c) = \mu_p p v^3_p+\frac{1}{2}\sigma_p^2 p^2 v^3_{pp}+\mu_c c v^3_c+\frac{1}{2}\sigma_c^2 c^2 v^3_{cc} \quad \text{for } p \leq 1 \text{ for all } c \in (0,\infty) \quad (C.9)$$

Solving first the homogeneous part of both $v^1(p,c)$ and $v^2(p,c)$, and then adding a particular solution for $v^1(p,c)$, we obtain:

$$v^1(p,c) = \frac{c}{r-\mu_c} - \frac{1}{r} + \hat{A}_1 c^{1+\eta_1} p^{-\eta_1} + \hat{A}_2 c^{1+\eta_2} p^{-\eta_2} \quad \text{for } p \geq c > 1 \quad (C.10)$$

and

$$v^2(p,c) = \hat{A}_3 c^{1+\eta_1} p^{-\eta_1} \quad \text{for } c \leq 1 \quad \text{and } p \in (0,\infty) \quad (C.11)$$

where:

$$\eta_1 = -\left(\frac{1}{2}+\frac{\mu_c-\mu_p}{\sigma_c^2+\sigma_p^2}\right)+\sqrt{\left(\frac{1}{2}+\frac{\mu_c-\mu_p}{\sigma_c^2+\sigma_p^2}\right)^2+\frac{2(r-\mu_c)}{\sigma_c^2+\sigma_p^2}} > 0 \quad (C.12)$$

$$\eta_2 = -\left(\frac{1}{2}+\frac{\mu_c-\mu_p}{\sigma_c^2+\sigma_p^2}\right)-\sqrt{\left(\frac{1}{2}+\frac{\mu_c-\mu_p}{\sigma_c^2+\sigma_p^2}\right)^2+\frac{2(r-\mu_c)}{\sigma_c^2+\sigma_p^2}} < 0 \quad (C.13)$$

By proceeding in the same way, we are able to obtain $v^3(p,c)$ and $v^4(p,c)$.

These are:

$$v^3(p,c) = \frac{p}{r-\mu_p} - \frac{1}{r} + \hat{B}_1 c^{1+\eta_1} p^{-\eta_1} + \hat{B}_2 c^{1+\eta_2} p^{-\eta_2} \quad \text{for} \quad c > p > 1 \quad (C.14)$$

and

$$v^4(p,c) = \hat{B}_3 c^{1+\eta_2} p^{-\eta_2} \quad \text{for } p \leq 1 \quad \text{and } c \in (0,\infty) \quad (C.15)$$

To determine the constants we compute the Matching Value and the Smooth Pasting conditions moving from one regime to the other. If both p and c are greater then one, the plant moves from $v^1(p,c)$ to $v^3(p,c)$ when $\frac{c}{p} = 1$. That is:

$$\frac{1}{r-\mu_c} + \hat{A}_1 + \hat{A}_2 = \frac{1}{r-\mu_p} + \hat{B}_1 + \hat{B}_2$$

$$\frac{1}{r-\mu_c} + (1+\eta_1)\hat{A}_1 + (1+\eta_2)\hat{A}_2 = (1+\eta_1)\hat{B}_1 + (1+\eta_2)\hat{B}_2$$

$$-\eta_1\hat{A}_1 - \eta_2\hat{A}_2 = \frac{1}{r-\mu_p} - \eta_1\hat{B}_1 - \eta_2\hat{B}_2$$

Let us now consider the case in which c becomes less than 1 (while $p > 1$). The plant stops producing and the value becomes $v^2(p,c)$. However, within this regime, the state variable that plays an important role in returning to produce is only c and not p. Thus, for any given value of p, the Matching Value condition and the Smooth Pasting condition are:

$$\frac{1}{r-\mu_c} - \frac{1}{r} + \hat{A}_1 p^{-\eta_1} + \hat{A}_2 p^{-\eta_2} = \hat{A}_3 p^{-\eta_1}$$

$$\frac{1}{r-\mu_c} + (1+\eta_1)\hat{A}_1 p^{-\eta_1} + (1+\eta_2)\hat{A}_2 p^{-\eta_2} = (1+\eta_1)\hat{A}_3 p^{-\eta_1}$$

Let us now consider the case where p becomes less than 1 (while $c > 1$). The plant is switched off and the value becomes $v^4(p,c)$. In this regime, the state variable that plays the role in returning to produce is p and not c. Then, for any given value of c, the Matching Value condition and the Smooth Pasting condition become:

$$\frac{1}{r-\mu_p} - \frac{1}{r} + \hat{B}_1 c^{1+\eta_1} + \hat{B}_2 c^{1+\eta_2} = \hat{B}_3 c^{1+\eta_2}$$

$$\frac{1}{r-\mu_p} - \eta_1\hat{B}_1 c^{1+\eta_1} - \eta_2\hat{B}_2 c^{1+\eta_2} = -\eta_2\hat{B}_3 c^{1+\eta_2}$$

The solution of the system is:

$$\hat{A}_1^{COAL} = A_{11}^{COAL} c^{-1-\eta_1} + A_{12}^{COAL} \quad (C.16)$$

$$= -\frac{r+\eta_2\mu_p}{(\eta_2-\eta_1)r(r-\mu_p)} c^{-1-\eta_1} + \frac{r-\mu_p-(1+\eta_2)(\mu_c-\mu_p)}{(\eta_2-\eta_1)(r-\mu_p)(r-\mu_c)} \quad (C.17)$$

$$\hat{A}_2^{COAL} = A_{21}^{COAL} p^{\eta_2} = -\frac{r-(1+\eta_1)\mu_c}{(\eta_2-\eta_1)r(r-\mu_c)} p^{\eta_2} \quad (C.18)$$

$$\hat{A}_3^{COAL} = A_{31}^{COAL} c^{-1-\eta_1} p^{\eta_1} + A_{32}^{COAL} p^{\eta_1} \quad (C.19)$$

$$= -\frac{r-\eta_2\mu_p}{(\eta_2-\eta_1)r(r-\mu_p)} c^{-1-\eta_1} p^{\eta_1} + \frac{r(1+\eta_2)-(1+\eta_1)(r-\mu_p)}{(\eta_2-\eta_1)r(r-\mu_p)} p^{\eta_1} \quad (C.20)$$

$$\hat{B}_1^{COAL} = B_{11}^{COAL} c^{-1-\eta_1} = -\frac{r+\eta_2\mu_p}{(\eta_2-\eta_1)r(r-\mu_p)} c^{-1-\eta_1} \quad (C.21)$$

$$\hat{B}_2^{COAL} = B_{21}^{COAL} p^{\eta_2} + B_{22}^{COAL} \quad (C.22)$$

$$= -\frac{r-(1+\eta_1)\mu_c}{(\eta_2-\eta_1)r(r-\mu_c)} p^{\eta_2} + \frac{r-\mu_p-(1+\eta_1)(\mu_c-\mu_p)}{(\eta_2-\eta_1)(r-\mu_p)(r-\mu_c)} \quad (C.23)$$

$$\hat{B}_3^{COAL} = B_{31}^{COAL} p^{\eta_2} c^{-1-\eta_2} + B_{32}^{COAL} c^{-1-\eta_2} \quad (C.24)$$

$$= -\frac{r-(1+\eta_1)\mu_c}{(\eta_2-\eta_1)r(r-\mu_c)} p^{\eta_2} c^{-1-\eta_2} - \frac{\eta_1\mu_c}{(\eta_2-\eta_1)r(r-\mu_c)} c^{-1-\eta_2} \quad (C.25)$$

Substituting and multiply for B, we obtain the expression in the text:

$$V_1^{COAL}(P,C,B) = \frac{C}{r-\mu_c} - \frac{B}{r} + A_{11}^{COAL} P^{-\eta_1} B^{\eta_1+1} + A_{12}^{COAL} P^{-\eta_1} C^{1+\eta_1} + A_{21}^{COAL} C^{1+\eta_2} B^{-\eta_2} \quad for\ P-B \geq C-B \quad (C.26)$$

$$V_2^{COAL}(C,B) = A_{31}^{COAL} B + A_{32}^{COAL} C^{1+\eta_1} B^{-\eta_1} \quad \text{for } C-B \leq 0 \ and\ \frac{P}{B} \in (0,\infty) \quad (C.27)$$

$$V_3^{COAL}(P,C,B) = \frac{P}{r-\mu_p} - \frac{B}{r} + B_{11}^{COAL} P^{-\eta_1} B^{\eta_1+1} + B_{21}^{COAL} C^{1+\eta_2} B^{-\eta_2} + B_{22} C^{1+\eta_2} P^{-\eta_2} \quad for\ C-B > P-B \quad (C.28)$$

$$V_4^{COAL}(P,B) = B_{31}^{COAL} B + B_{32}^{COAL} P^{-\eta_2} B^{1+\eta_2} \quad \text{for } P-B \leq 0 \ and\ \frac{C}{B} \in (0,\infty) \quad (C.29)$$

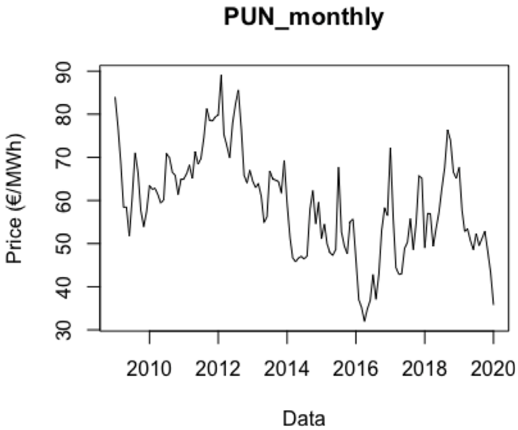

Fig. D.12. Monthly PUN prices.

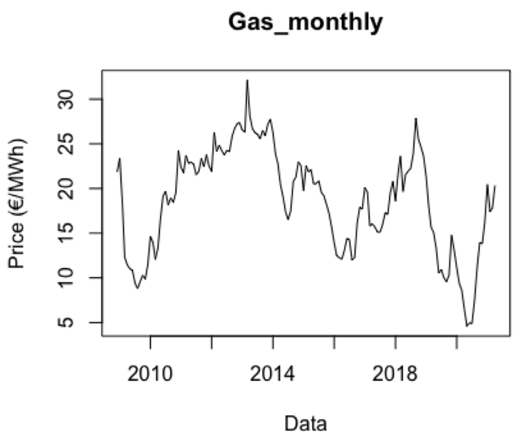

Fig. D.13. Monthly TTF Gas prices.

Appendix D. GBM DF test

The PUN time series was downloaded from the GME website (Gestore Mercati Energetici) at the following link https://www.mercatoelettrico.org/it/download/DatiStorici.aspx. This is a time series of hourly prices and starts from 01/01/2009. The time series of gas prices was obtained from the Eikon database. Specifically, these are the returns of the day-ahead price of natural gas traded on the TTF[29] (TTF Spot Price — Day-Ahead). In this case, they are time series of daily prices and starts from 01/12/2008. The API2 Futures time series can be downloaded at the following link https://it.investing.com/commodities/coal-(api2)-cif-ara-futures. The prices are daily and start from 01/01/2015.

Starting from these time series, for all of them monthly price averages were then calculated. In Figs. D.12, D.13 and D.14 are represented the monthly average prices for PUN, TTF Day-ahead Natural Gas and Coal (API2) Futures, respectively.

A Dickey–Fuller test (unit root test with constant) was applied in order to study if the time series retrieved for P, C and B follow a GBM. The Dickey–Fuller test is normally used for testing the null hypothesis that a unit root is present in the auto-regression process of the time series considered. The simplest version of the DF test is a simple AR(1) model i.e. $y_t = \rho y_{t-1} + u_t$ where y_t is the variable of interest, t is the time index, ρ is the coefficient and u_t is the error term. If $\rho = 1$ then

[29] TTF or Title Transfer Facility is the virtual point of delivery within the National Gas Transmission System.

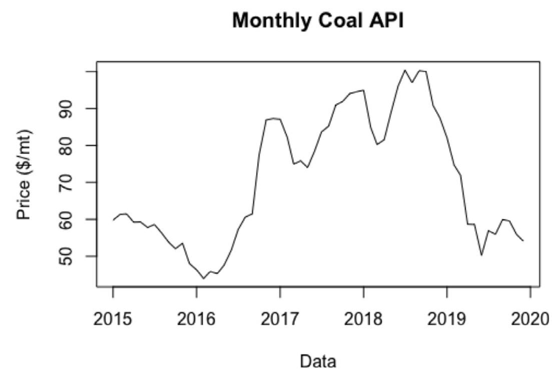

Fig. D.14. Monthly API2 Futures prices.

a unit root is present, in this case the time series is non-stationary. In our analysis we adopted the so called DF unit root test with constant, i.e. $y_t = a_0 + \rho y_{t-1} + u_t$.

Starting from Eq. (4), (5) and (28) and applying Ito's formula, we can rewrite the three equations as:

$$dlnP_t = \left(\mu_P - \frac{\sigma_P^2}{2}\right) dt + \sigma_P dW_t^P \tag{D.1}$$

$$dlnC_t = \left(\mu_C - \frac{\sigma_C^2}{2}\right) dt + \sigma_C dW_t^C \tag{D.2}$$

$$dlnB_t = \left(\mu_B - \frac{\sigma_B^2}{2}\right) dt + \sigma_B dW_t^B \tag{D.3}$$

By considering monthly average price series, we test for unit roots by modeling the differential equations as:

$$\ln P_t - \ln P_{t-1} = a_0 + (\delta - 1) \ln P_{t-1} + e_t \tag{D.4}$$

$$\ln C_t - \ln C_{t-1} = b_0 + (\delta - 1) \ln C_{t-1} + z_t \tag{D.5}$$

$$\ln B_t - \ln B_{t-1} = c_0 + (\delta - 1) \ln B_{t-1} + k_t \tag{D.6}$$

Where $a_0 = \left(\mu_P - \frac{\sigma_P^2}{2}\right)$, $b_0 = \left(\mu_C - \frac{\sigma_C^2}{2}\right)$, $c_0 = \left(\mu_B - \frac{\sigma_B^2}{2}\right)$, $e_t = \sigma_P \epsilon_t$, $z_t = \sigma_C \epsilon_t$, $k_t = \sigma_B \epsilon_t$ and $\epsilon_t \sim N(O, 1)$.

The null hypothesis is that lnP_t, lnC_t and lnB_t have a unit root, $H_0 : \delta = 1$, while the alternative hypothesis is $H_1 : \delta < 1$. If H_0 is accepted then the process is GBM.

In the three tables below are reported the results obtained for P_t, C_t and B_t respectively. In particular:

- for P_t at a confidence level of 1%, the null hypothesis (H_0) of the presence of a unit root can be accepted since the critical value obtained is greater than the respective critical value, $-2.9333 > -3.46$.
- for C_t, H_0 at a confidence level of 10% can be accepted since the critical value obtained is greater than the respective critical value, $-1.8956 > -2.57$.
- for B_t, H_0 at a confidence level of 10% the hypothesis H_0 can be accepted since the critical value obtained is greater than the corresponded critical value, $-0.938 > -2.58$.

Both monthly and yearly drift and diffusion terms are computed. The results of parameter estimations for the day-ahead electricity price P, the natural gas price C and the carbon price B are summarized in Table 4.

Appendix E. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.eneco.2024.107882.

Table 4
Dickey–Fuller test results and GBM parameters estimation.

Time series	GBM				
	DF	μ		σ	
		monthly	yearly	monthly	yearly
PUN	−2.93	−0.0642%	−0.7708%	10.78%	37.37%
TTF Spot Price	−1.89	−0.0499%	−0.5989%	10.61%	36.75%
API2 Futures	−0.94	0.0801%	0.9619%	7.08%	24.53%

References

Andreis, L., Flora, M., Fontini, F., Vargiolu, T., 2020. Pricing reliability options under different electricity price regimes. Energy Econ. 87, 104–705.

Askeland, M., Jaehnert, S., Korpas, M., 2017. Equilibrium assessment of storage technologies in a power market with capacity remuneration. Sustain. Energy Technol. Assess. 31, 228–235.

Bersani, A.M., Falbo, P., L., M., 2022. Is the ETS an effective environmental policy? Undesired interaction between energy-mix, fuel-switch and electricity prices. Energy Econ. 110, 105981.

Bhagwat, P.C., de Vries, L.J., 2013. The effect of German strategic reserves on the central European electricity market. In: 2013 10th International Conference on the European Energy Market. EEM, pp. 1–7.

Bolton, R., Clausen, T., 2019. Ambiguous interventions: Capacity remuneration mechanisms and the politics of energy transition in Britain and Germany. Energy Res. Soc. Sci. 56, 101218.

Bonaldo, C., Caporin, M., Fontini, F., 2022. The relationship between day-ahead and future prices in electricity markets: An empirical analysis on Italy, France, Germany, and Switzerland. Energy Econ. 110.

Borovkova, S., Schmeck, M.D., 2017. Electricity price modeling with stochastic time change. Energy Econ. 63, 51–65.

Bowring, J.E., Gramlich, R.E., 2000. The role of capacity obligations in a restructured Pennsylvania-New Jersey-Maryland electricity market. Electricity J. 13 (9), 57–67.

Bublitz, A., Keles, D., Zimmermann, F., Fraunholz, C., Fichtner, W., 2019. A survey on electricity market design: Insights from theory and real-world implementations of capacity remuneration mechanisms. Energy Econ. 80, 1059–1078.

Burger, M., Klar, B., Mueller, A., Schindlmayr, G., 2004. A spot market model for pricing derivatives in electricity markets. Quant. Finance 4, 109–122.

Caporin, M., Fontini, F., Segato, S., 2021. Has the EU-ETS financed the energy transition of the Italian power system? Int. J. Financ. Stud. 9, 1–15.

Caputo, A., 2017. Fattori Di Emissione Atmosferica Di CO2 E Altri Gas a Effetto Serra Nel Settore Elettrico. Annual Report 257/17, Istituto Superiore per la Protezione e la Ricerca Ambientale - ISPRA.

Creti, A., Fontini, F., 2019. Economics of Electricity Markets, Competition and Rules. Cambridge University Press.

Detemple, J., Kitapbayev, Y., 2020a. The value of green energy: Optimal investment in mutually exclusive projects and operating leverage. Rev. Financ. Stud. 33, 3307–3347.

Detemple, J., Kitapbayev, Y., 2020b. The value of green energy under regulatory uncertainty. Energy Econ. 89.

Finon, D., Pignon, V., 2008. Electricity and long-term capacity adequacy: The quest for regulatory mechanism compatible with electricity market. Util. Policy 16 (3), 143–158, Capacity Mechanisms in Imperfect Electricity Markets.

Fontini, F., Vargiolu, T., Zormpas, D., 2021. Investing in electricity production under a reliability options scheme. J. Econom. Dynam. Control 126.

Fraunholz, C., Keles, D., Fichtner, W., 2021. On the role of electricity storage in capacity remuneration mechanisms. Energy Policy 149, 112014.

Fu-Wei, H., Shi, C., Jyh-Horng, L., 2022. Free riding and insurer carbon-linked investment. Energy Econ. 107, 105838.

Genoese, M., Genoese, F., Fichtner, W., 2012. Model-based analysis of the impact of capacity markets on electricity markets. In: 2012 9th International Conference on the European Energy Market. pp. 1–6.

Gerres, T., Chaves Ávila, J.P., Martín Martínez, F., Abbad, M.R., Arín, R.C., Sánchez Miralles, Á., 2019. Rethinking the electricity market design: Remuneration mechanisms to reach high RES shares. Results from a Spanish case study. Energy Policy 129, 1320–1330.

Höschle, H., De Jonghe, C., Six, D., Belmans, R., 2015. Capacity remuneration mechanisms and the transition to low-carbon power systems. In: 2015 12th International Conference on the European Energy Market. EEM, pp. 1–5.

International Energy Agency (IEA), 2021. World Energy Outlook 2021.

Khalfallah, M., 2009. Long term capacity adequacy in electricity markets: Reliability contracts VS capacity obligations. Energy Stud. Rev. 16, 1–37.

Khan, A., Verzijlbergh, O., De Vries, L., 2018. How do demand response and electrical energy storage affect (the need for) a capacity market? Appl. Energy 214, 39–62.

Kozlova, M., 2017. Electricity price modeling with stochastic time change. Renew. Sustain. Energy Rev. 80, 180–196.

Kozlova, M., Huhta, K., Lohrmann, A., 2023. The interface between support schemes for renewable energy and security of supply: Reviewing capacity mechanisms and support schemes for renewable energy in Europe. Energy Policy 181, 113707.

Kozlova, M., Overland, I., 2022. Combining capacity mechanisms and renewable energy support: A review of the international experience. Renew. Sustain. Energy Rev. 155, 111878.

Minkea, C., Tureka, T., 2018. Materials, system designs and modelling approaches in techno-economic assessment of all-vanadium redox flow batteries – A review. J. Power Sources 376, 66–81.

Nordhaus, W., 2017. Revisiting the social cost of carbon. Proc. Natl. Acad. Sci. 114, 1518–1523.

Poli, N., Bonaldo, C., Moretto, M., Guarnieri, M., 2024. Techno-economic assessment of future vanadium flow batteries based on real device/market parameters. Appl. Energy 362, 122954.

Poli, N., Bonaldo, C., Trovò, A., Guarnieri, M., 2021. Optimal energy storage systems for long charge/discharge duration. In: ICAE 2021 International Conference on Applied Energy.

Schiffer, Hans-Wilhelm, D., 2015. Europe's road to a sustainable energy-supply system. Energy Environ. 26, 111–126.

Schröder, T., Kuckshinrichs, W., 2015. Value of lost load: An efficient economic indicator for power supply security? A literature review. Front. Energy Res. 3.

Simoglou, C.K., Biskas, P.N., 2023. Capacity mechanisms in Europe and the US: A comparative analysis and a real-life application for Greece. Energies 16.

Tan, X., Sirichand, K., Vivian, A., Wang, X., 2020. How connected is the carbon market to energy and financial markets? A systematic analysis of spillovers and dynamics. Energy Econ. 90, 104870.

Yarrow, G., 2003. Capacity auctions in the UK energy sector. Util. Policy 11 (1), 9–20, Auctions of Capacity in Network Industries.

Zero Emissions Platform (ZEP), 2013. ZEP Market Economics Report.

Zhang, H., Jin, G., Zhang, Z., 2021. Coupling system of carbon emission and social economy: A review. Technol. Forecast. Soc. Change 167, 120730.