The World's Largest Open Access Agricultural & Applied Economics Digital Library

This document is discoverable and free to researchers across the globe due to the work of AgEcon Search.

Help ensure our sustainability.

Give to AgEcon Search

AgEcon Search
http://ageconsearch.umn.edu
aesearch@umn.edu

*Papers downloaded from **AgEcon Search** may be used for non-commercial purposes and personal study only. No other use, including posting to another Internet site, is permitted without permission from the copyright owner (not AgEcon Search), or as allowed under the provisions of Fair Use, U.S. Copyright Act, Title 17 U.S.C.*

No endorsement of AgEcon Search or its fundraising activities by the author(s) of the following work or their employer(s) is intended or implied.

July 2022

Fondazione Eni Enrico Mattei

Working Paper

016.2022

The Energy Transition and the Value of Capacity Remuneration Mechanisms

Cinzia Bonaldo, Fulvio Fontini, Michele Moretto

The Energy Transition and the Value of Capacity Remuneration Mechanisms

By **Cinzia Bonaldo**, Department of Management Engineering, University of Padua
Fulvio Fontini, Department of Economics and Management and Interdepartmental Centre "Giorgio Levi Cases" for Energy Economics and Technology, University of Padua
Michele Moretto, Department of Economics and Management, Interdepartmental Centre "Giorgio Levi Cases" for Energy Economics and Technology, University of Padua and Fondazione Eni Enrico Mattei (FEEM)

Summary

Capacity Remuneration Mechanisms (CRM) can be used in power markets to overtake market failures, reaching security of supply. However, investment in capacity is a dynamic process, that depends on the evolution of prices and costs overtime. In our paper we study the capacity remuneration value through a CRM depending on three possible different technologies that participate to the market: a Variable Renewable Energy (VRE) source; a thermal efficient plant (i.e. Combine Cycle Gas Turbine) and a brown plant (i.e. coal). We shall see that these three types of capacities can be framed by means of a common theoretical framework, whose level of complexity increases as the uncertainty rises, moving from the simplest scheme (VRE technology) to the most complex one (coal power plant). For these different technological provisions, we consider how to evaluate them focusing on their investment value by adopting a stochastic approach; we first provide a theoretical framework and then sensitivity analysis and calibration results. We show that for all three technology considered the effect of the CRM is to cap the firm revenues and as consequence it decreases their value.

Keywords: energy transition, capacity remuneration mechanism, price cap, renewable energies, investment value

JEL Classification: Q40, C60, D80

***Address for correspondence*:**
Cinzia Bonaldo
Department of Management Engineering, University of Padua
Italy – Via Venezia 1, 35131 Padova
e-mail: cinzia.bonaldo@phd.unipd.it

The opinions expressed in this paper do not necessarily reflect the position of Fondazione Eni Enrico Mattei

The Energy Transition and the Value of Capacity Remuneration Mechanisms

Cinzia Bonaldo[1], Fulvio Fontini[2,3], and Michele Moretto[2,3,4]

[1] *Department of Management Engineering, University of Padua, Italy*
[2] *Department of Economics and Management, University of Padua, Italy*
[3] *Interdepartmental Centre "Giorgio Levi Cases" for Energy Economics and Technology, University of Padova, Padova, Italy*
[4] *FEEM, Fondazione Enrico Mattei, Milano, Italy*

Abstract

Capacity Remuneration Mechanisms (CRM) can be used in power markets to overtake market failures, reaching security of supply. However, investment in capacity is a dynamic process, that depends on the evolution of prices and costs overtime. In our paper we study the capacity remuneration value through a CRM depending on three possible different technologies that participate to the market: a Variable Renewable Energy (VRE) source; a thermal efficient plant (i.e. Combine Cycle Gas Turbine) and a brown plant (i.e. coal). We shall see that these three types of capacities can be framed by means of a common theoretical framework, whose level of complexity increases as the uncertainty rises, moving from the simplest scheme (VRE technology) to the most complex one (coal power plant). For these different technological provisions, we consider how to evaluate them focusing on their investment value by adopting a stochastic approach; we first provide a theoretical framework and then sensitivity analysis and calibration results. We show that for all three technology considered the effect of the CRM is to cap the firm revenues and as consequence it decreases their value.

Keywords— energy transition, capacity remuneration mechanism, price cap, renewable energies, investment value

1 Introduction

The energy transition challenge calls for a rise of the share of power for final energy usages, as well as an increase of power generation from renewable energy sources. In Europe, for instance, the *fit for 55* package of the European Commission prescribes that by 2030, 65% of electricity in Europe will have to be generated by renewable energy sources, which implies the need to install roughly 450 GW of new renewable capacity. [1] The rising penetration of renewable energy sources however impacts on the security of supply risk for power system, due to the increase of non-controllable small scale Variable Renewable Energy sources (VRE) which implies higher balancing need, as well as higher price volatility (Bonaldo et al. (2022)). At the same time, controllable back-up capacity, which is mostly supplied by thermal power plants due to the limited impact of power storage,[2] faces reduced incentives to remain on line or be built due to the rise of investment risks. Thus, there seems to be a trade-off between the rising need of power supplied by VRE and the security of supply challenges that this poses to power systems. A possible way to reconcile the trade-off calls for the implementation of Capacity Remuneration Mechanisms (CRM) that can favour investments. Indeed, it is a well-known theoretical result of the market design theory that in a first-best world, power markets with CRM provide the same optimal level of adequacy of energy markets without CRM, the so-called energy-only markets (Creti and Fontini (2019)). However, load rigidity, increasing risks and difficulties in assessing the value for consumers of the energy shed (the so-called Value of Loss Load, VOLL) can justify the implementation of CRM (Joskow and Tirole (2007), Joskow (2008), Joskow and Wolfram (2012), Cramton et al. (2013)). There exists several types of CRMs: *capacity payments*, which are payments for capacity administratively set; *capacity auctions*, procurement auctions through which the System Operator (SO)[3] remunerates a given amount of generation capacity; *reliability options*, contracts sold by power producers to the SO in exchange for a premium, that obliges the seller of the reliability option 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; *capacity obligation*, which is the obligation for load serving entities to hold enough capacity to serve the load; *strategic reserves*, which are power plants withdrew from the

[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).

market and divested to the SO, that uses it whenever there is a security of supply threat. In all those cases, the effect of the introduction of a CRM is to impose *de facto* a price cap to power market: the increase of capacity rises power supplied, which implies that the electricity price does not spike to the level of the willingness to pay for the first unit of power not served but remains to the marginal cost of the last unit of power supplied.[4] Therefore, the marginal cost of the last plant dispatched, i.e., the marginal plant, provides the effective price cap of markets with CRM.

Even if CRM 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. The investments that they bring about have expected life-times and need to be amortized on a sufficiently long time scale. Therefore, the capacity that is brought in line thanks to the CRM, even if it can provide the optimal level of security of supply, i.e., providing enough energy when needed (with the consequence of capping energy price, as explained), it also introduces a rigidity in the power system, by fixing the set of power plants that are brought in line or maintained active. This in turns implies that the power system loses the possibility to gain from investments' cost reductions, accruing for instance from a technological evolution. In other words, CRMs imply a loss of flexibility of investing in the future under different circumstances. Thus a different trade-off arises between security of supply and the benefit of technological evolution. In this paper, we consider this trade-off studying the value of the investment in different types of power capacity that are incentivized by the CRM. Indeed, a CRM can be technology specific or technology neutral. In the first case, the capacity remuneration can be reserved to a specific type of investments. Examples of these are capacity auctions reserved to VRE, to Demand Side Response (DSR) or strategic reserves targeted to specific types of power plants. It is also possible that the CRM regulation prescribes such a broad range of technical prerequisite for the capacity that different technologies can participate. In this case, the technology that is remunerated is the one with the least capacity cost per unit of power supplied.[5] In any case, depending on the cost structure of a given power system, or on the specific CRM regulation, it is well possible that different technologies receive distinct incentives. 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 favoured or disadvantaged vs. hydrocarbon-fired plants. Evaluating to what extent a CRM can favour 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

[4]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, that would 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.

[5]This has been the case, for instance, of the Italian capacity auction of Reliability Options held in year 2019, in which the awarded capacity was all from gas-fired plants.

paper. In order to distinguish between capacity that favour energy transition and capacity that can lock-in the technological evolution, we consider three possible types of capacity participation to CRM:

1. a capacity that enables supplying firm energy from VRE 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 Combine Cycle Gas Turbine (CCGT) 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 (NPV), adopting a stochastic approach. We first provide a theoretical framework, 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, assuming that the random cost component is give by coal in the third model. 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. Finally, 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 social welfare 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 summarise the relevant literature. Section 3 address the investment problem under a CRM: the economic dispatching principle of competitive energy market is presented as well as the different sources of uncertainty faced by a power plant investor. Section 4 introduces multi-period valuation models under the assumption that plants' revenues and costs evolve stochastically, introducing the three models characterized by an increasing level of complexity. In Section 5 we fit the stochastic processes used by means of empirical data and then estimate the models' parameters considered. Models' calibration and sensitivity analyses are also provided and discussed. Section 6 presents the results of the evaluation of each model relating it to the energy transition, followed by final remarks and suggestions for futures studies. Proofs of the Propositions and time series analysis are in the Appendix.

2 Literature review

There exists a vast literature on CRMs that focuses on their need and effectiveness as investment incentives to deliver security of supply (Cramton et al. (2013), Spees et al. (2013), Roques (2008)) and on specific markets' analyses (United Kingdom Bhagwat et al. (2017), Germany Neuhoff et al. (2016), Ozdemir et al. (2013), Italy Mastropietro et al. (2018) , Ireland and others Hancher et al. (2015), Poland Przemyslaw et al. (2021), the United States Lin and Vatani (2017), Bowring (2013), and other markets throughout the world Galetovic et al. (2015), Ashokkumar et al. (2020)). A smaller set of works analyze quantitatively the option value of the power capacity. Andreis et al. (2020) provide semi explicit formulae to evaluate the option value of a Reliability Option under different assumptions for the underlying stochastic process of the electricity prices. Sezgen et al. (2007) evaluate the options which are implicit in DSR mechanisms. Burger et al. (2004), through a Monte Carlo approach, evaluated capacity as a bundle of call options on hourly prices. Other authors focused on the relationship between electricity security of supply and CRM. In Khalfallah (2009), the author analyzed two different incentive mechanisms, i.e. reliability contracts and capacity obligations, and compared them to the energy-only market. Then, a backward stochastic dynamic programming method is applied to solve the investment problem. The model allows to identify at which load and fuel price levels it is optimal to invest in a new power plant. In Fraunholz et al. (2021), the authors evaluates how the specific design of a CRM can create a bias against electricity security of supply and thereby affect future technology mix as well as long-term generation adequacy. In Khan et al. (2018), the authors investigated how pumped storage and demand side response should be remunerated by a capacity markets. They present a hybrid optimization model with agents making investment decisions to maximize future profits provide simulated results. Askeland et al. (2017) set up a linear complementary model to study both an energy-only market and a market with CRM. For each of the two market configurations, different storage possibilities are analyzed, by means of lead-acid batteries and pumped storage are analyzed. The authors find that batteries can be a cost-effective alternative to thermal power generation to serve the peak load and contribute to a capacity reserve requirement. However, none of the studies considered evaluate explicitly the role of technological lock-in induced by the CRM or perform a comparative evaluation of the different technologies to deliver security of supply, as we do here.

3 The investment problem

Operating a power plant in the electricity market brings about several sources of risk. A first source of risk derives from the economic dispatching principle of competitive energy market. This implies that the price of energy is given by the marginal cost of the marginal technology, i.e., the technology that is providing the last unit of energy to serve the load, as long as there is some spare capacity, namely, there exist the possibility to increase generation should the load rise. When the system is running short of capacity, that is, it is using all of its capacity, the energy price spikes to the value of the first unit of energy not served, the so-called Value of Lost Load (VOLL).[6] If there are CRM, the latter affect the dynamics of the power prices. If a CRM provides (optimal) security of supply this means that there is enough capacity and thus the would be no price spiking to the VOLL. The power price would be effectively capped at the level of the marginal cost of the marginal plant (the plant with the highest marginal cost), whenever the system would have seen a spike in the energy price to the VOLL had the CRM not being in place. This is the price cap effect of the CRM[7]. When an investor invest in capacity under a CRM, obtains ex ante a remuneration for it, the capacity premium, but gives up the extra profits that it would have faced when the system would have gone to the VOLL because of the shortage of capacity, but does not, thanks to the CRM (the price cap effect). Thus, the investor bears two sources of uncertainty: the uncertainty due to the dynamic of the energy price, and the uncertainty due to the dynamic of the price cap effect. This latter depends in turn 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. The investment under a CRM framework thus effectively implies a further source of uncertainty for an investor: at the time of the investment, it has to foresee the likelihood that it will be dispatched in the energy market, which depend on the comparison between its own marginal cost and both the forecasted energy prices and the forecasted price cap effect. In other words, when it invests, it needs to foresee to what extent it is efficient at that time and will remain such throughout the entire life-cycle of its investment. This clearly depends on its own actual cost, on how its own generation costs will evolve overtime and on the technological development which will affect the system costs and therefore will determine the evolution of the price cap effect and on the duration of the CRM mechanisms. The longer the time commitment of the capacity, the higher the risk that eventually the power plant that it has been invested on will be overtaken by more efficient plants, which implies loosing the supermarginal operating profits that benefit inframarginal technologies.

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[8]. In this paper, we shall neglect this, assuming that investment costs in a given power plant are know, even if they differ across technologies. Also the amount of the CRM is known. We focus on the uncertainty that comes from

[6]In real life, before going to the VOLL the system would see some security margin constraints violated. The price would spike (at the level of the value of the first unit of energy not served) due to the system security violation. This implies that the price would tend to the VOLL, without reaching it.

[7]See Creti and Fontini (2019) for further explanations.

[8]This will be the case, for instance, of capacity auctions, that are run after that a given investment has been brought in line.

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 a permanent commitment to generate power, i.e., we assume an infinite horizon.[9] We shall consider three different technologies. They can be seen as a model with an increasing level of uncertainty about market operation. 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.[10] Such a model represents a firm capacity supplied by a VRE. In general, VRE are characterized by limited controllability, since typically the investor does not control the supply of the primary energy source they recall on. The guiding principle of CRMs is to incentivise capacity that generates energy when needed, and for this, often penalties for unavailabilities are set or technical requirements are introduced such that only controllable capacity that can be planned in advanced can participate to the CRM. A possible solution for VRE to provide such a capacity is coupling it to some storage facility, which would allow it to get rid of the cycle of availability of the primary energy (as it is for instance for the case of photo-voltaic plants) or eliminate the forecast risk (as it is the case of the wind power supply), as long as the storage facility is large and reliable enough. Not all types of storage facilities could provide this. For instance, lithium-ion batteries typically have limited capacity supply, specific and constrained charging cycles, are subject to decay and have short expected life-time. Thus they might not be suitable to participate to the CRM, in particular for those CRMs that require a long-term commitment. New forms of storage technologies are emerging that can get rid of these limitations. They are termed Long Duration Energy Storage (LDES) means.[11] Several technologies allow to privide these kind of service. In a nutshell, they allow converting electricity into another vector that provides a stock of energy stored, and which can be easily inverted to generate again the flow of energy. Examples of such vectors are compressed air, heat, hydrogen of chemical components stored in Redox Flow batteries. This is the type of storage that we have in mind. In this model, we are assuming that a storage facility coupled with VRE exists, that can provide long-term energy storage with no decay, for any possible capacity-energy ratio

[9]Even if this is not what occurs in real world, it can be representative of those CRM 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.

[10]For simplicity we are assuming that even in the case of null system price it has priority dispatching. 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.

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

required, which implies that charging and discharging cycles can be planned in advance without any risk of security of supply, as it is the case, for instance for the Vanadium Redox Flow Batteries (Bonaldo and Poli (2022)) and with no unavailability risk. 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. This is the first model we shall consider.

A first degree of complexity is added when 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 overtime the own generation cost rise 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, 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 overtime, there will always be some other power plant whose marginal cost will be higher than its own one. 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 off-line earlier than the new investment, or that overtime new efficient plant come in line and crowd it out the investment. We neglect these possibilities here for the sake of simplicity, and focus on an investment that does not reasonably see any quantity risk accruing from the price cap effect. To help framing this case, we shall refer to it as the investment in an efficient Combined Cycle Gas Turbine (CCGT) plant in a system which is largely gas-based. Finally, 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 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.[12] We do not consider this aspect here, and focus on a capacity which has a positive marginal cost, which might eventually be displaced by some other power supply in the merit order, but whose cost dynamics is not correlated to the system marginal price one. 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 depends also on the regulatory and technological evolution. This implies that overtime 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 framing 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.

4 Analytical framework

4.1 Model 1: VRE coupled with an efficient ESS

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 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) C_t. 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.[13]

As mentioned, in this model there are no variable costs of power generation. The Net Present Value are 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, being the operating cost null. The operating profits, however are influenced by the existence of the CRM. In particular, two regime arises. Whenever

[12] There exist a large literature on the estimate of electricity costs pass-through, that we cannot review here. See for instance Caporin et al. (2021) and references therein.

[13] 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.

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 makes sure that there is at the margin enough capacity, and thus the price is given by the marginal cost of the (least efficient) marginal technology. It is the price cap effect, which becomes binding when $P_t \geq C_t$. In Figure (1) are represented revenues for this technology.

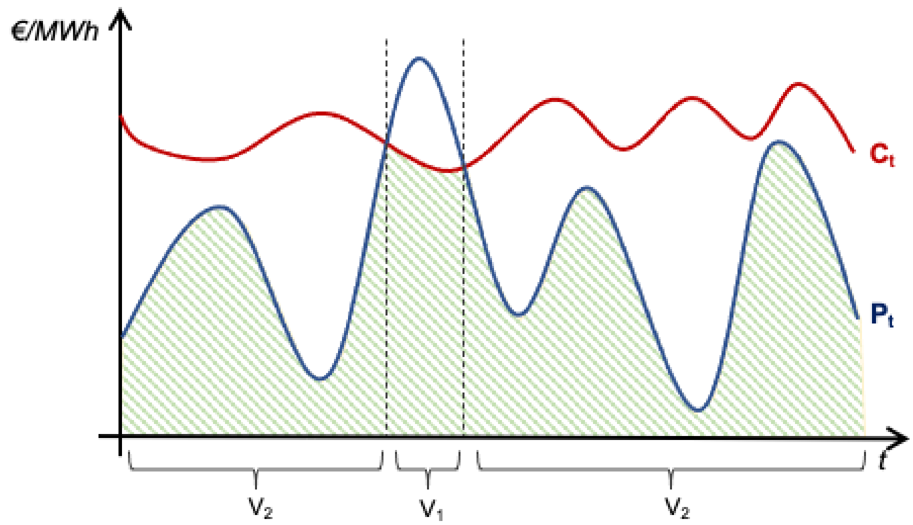

Figure 1: The green area represent the operating profits for a firm capacity supplied by a VRE under the existence of the CRM. The x-axis corresponds to time t, the y-axis are revenues, measured in Euro/MWh. The red line represents the marginal costs of the marginal technology, C_t; the blue line represents the day-ahead electricity prices P_t. The vertical dashed lines identify the regimes of the value function, as described by equation (6).

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

$$\pi_t^{VRE} = \min(P_t,\ C_t) \tag{1}$$

or, more specifically:

$$\pi_t^{VRE} = \begin{cases} C_t & \text{if } P_t \geq C_t \\ P_t & \text{if } P_t < C_t \end{cases} \tag{2}$$

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): [14]

$$\frac{dP_t}{P_t} = \mu_P P_t dt + \sigma_P P_t dW_t^P \quad \text{with } P_0 = P \tag{3}$$

$$\frac{dC_t}{C_t} = \mu_c C_t dt + \sigma_c C_t dW_t^C \quad \text{with } C_0 = C \tag{4}$$

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.[15]

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[16] 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 present value of the latter is thus given by the following equation:

$$V^{VRE}(P,C) = E_0 \left[\int_0^\infty \min(P_t,\ C_t) e^{-rt} dt \right] \tag{5}$$

where $E_0(\cdot)$ 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 fot the value function $V^{VRE}(P,C)$ distinguishing the case in which $P \geq C$ or

[14] 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) Borovkova and Schmeck (2017)). Andreis et al. (2020) 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.

[15] 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.

[16] 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}.

$P < C$. Provided that $r - \mu_P > 0$ and $r - \mu_C > 0$, the following Proposition summarizes the solution of (5), hereafter we drop the time index when this does not cause confusion.
Proposition 1. *The NPV of the investment in the case of firm capacity supplied by VRE is:*

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

with:

$$V^{VRE}(P,C) = \begin{cases} V_1^{VRE} = \frac{C}{r-\mu_C} + A^{VRE} C^{1+\beta_1} P^{-\beta_1} & \text{for } P \geq C \\ V_2^{VRE} = \frac{P}{r-\mu_P} + B^{VRE} C^{1+\beta_2} P^{-\beta_2} & \text{for } P < C \end{cases} \tag{6}$$

Where:

$$A^{VRE} = \frac{(r-\mu_C) + \beta_2(\mu_P - \mu_C)}{(\beta_2 - \beta_1)(r-\mu_P)(r-\mu_C)} \tag{7}$$

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

and

$$\beta_1 = -\left(\frac{1}{2} + \frac{\mu_C - \mu_P}{\sigma_C^2 + \sigma_P^2}\right) + \sqrt{\left(\frac{1}{2} + \frac{\mu_C - \mu_P}{\sigma_C^2 + \sigma_P^2}\right)^2 + \frac{2(r-\mu_C)}{\sigma_C^2 + \sigma_P^2}} > 0 \tag{9}$$

$$\beta_2 = -\left(\frac{1}{2} + \frac{\mu_C - \mu_P}{\sigma_C^2 + \sigma_P^2}\right) - \sqrt{\left(\frac{1}{2} + \frac{\mu_C - \mu_P}{\sigma_C^2 + \sigma_P^2}\right)^2 + \frac{2(r-\mu_C)}{\sigma_C^2 + \sigma_P^2}} < 0 \tag{10}$$

Poof: 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 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 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. In Section 5.2 below we discuss their value, sign and present a sensitivity analysis with respect to $r - \mu_P$ and $r - \mu_C$. We shall also calibrate the level of the value function V^{VRE}, and show how it changes depending on the drifts, μ_P and μ_C, and the volatilities σ_P and σ_C.

4.2 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 the 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[17]. Thus in this third regime the plant would not have any operating profits. Figure 2 represents the operating profits for this type of technology.

[17]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.

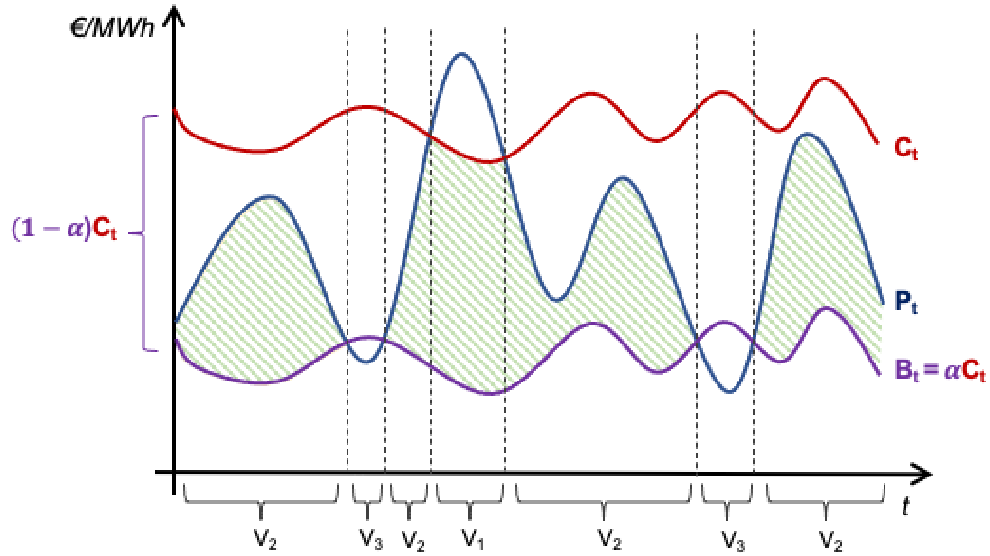

Figure 2: The green area represent the operating profits for a firm capacity supplied by a CCGT power plant under the existence of the CRM. The x-axis corresponds to time t, the y-axis are Euro/MWh. The red line represents the marginal costs of the marginal technology, C_t; the blue line represents the day-ahead electricity prices P_t; the cost of generating power from the CCGT is given by the purple curve αC_t. The vertical dashed lines identify the regimes of the value function, as described by equation (14).

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

$$\pi_t^{CCGT} = \max[\min(P_t,\ C_t) - \alpha C_t,\ 0] \tag{11}$$

or, more specifically:

$$\pi_t^{CCGT} = \begin{cases} C_t - \alpha C_t & \text{if } \ P_t \geq C_t \\ P_t - \alpha C_t & \text{if } \ \alpha C_t < P_t < C_t \\ 0 & \text{if } \ P_t < \alpha C_t \end{cases} \tag{12}$$

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:

$$V^{CCGT}(P, C) = E_0 \left[\int_0^{\infty} \max[\min(P_t,\ C_t) - \alpha C_t,\ 0] e^{-rt} dt \right] \tag{13}$$

Following the same procedure as before, we can calculate the value function $V^{CCGT}(P,C)$ 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 (13):

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

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

with

$$V^{CCGT}(P,C) = \begin{cases} V_1^{CCGT}(P,C) & \text{for } P \geq C \\ V_2^{CCGT}(P,C) & \text{for } \alpha C < P < C \\ V_3^{CCGT}(P,C) & \text{for } \ P < \alpha C \end{cases} \tag{14}$$

and

$$V_1^{CCGT}(P,C) = \frac{(1-\alpha)C}{r-\mu_C} + A_1^{CCGT} C^{1+\beta_1} P^{-\beta_1} \tag{15}$$

$$V_2^{CCGT}(P,C) = \frac{P}{r-\mu_P} - \frac{\alpha C}{r-\mu_C} + A_2^{CCGT} C^{1+\beta_1} P^{-\beta_1} + B_2^{CCGT} C^{1+\beta_2} P^{-\beta_2} \tag{16}$$

$$V_3^{CCGT}(P,C) = B_3^{CCGT} C^{1+\beta_2} P^{-\beta_2} \tag{17}$$

Where the four constants are given by:

$$A_1^{CCGT} = \frac{(r-\mu_C)+\beta_2(\mu_P-\mu_C)}{(\beta_2-\beta_1)(r-\mu_P)(r-\mu_C)}(1-\alpha^{\beta_1+1}) \tag{18}$$

$$A_2^{CCGT} = -\frac{(r-\mu_C)+\beta_2(\mu_P-\mu_C)}{(\beta_2-\beta_1)(r-\mu_P)(r-\mu_C)}\alpha^{\beta_1+1} \tag{19}$$

$$B_2^{CCGT} = \frac{(r-\mu_C)+\beta_1(\mu_P-\mu_C)}{(\beta_2-\beta_1)(r-\mu_P)(r-\mu_C)} \tag{20}$$

$$B_3^{CCGT} = \frac{(r-\mu_C)+\beta_1(\mu_P-\mu_C)}{(\beta_2-\beta_1)(r-\mu_P)(r-\mu_C)}(1-\alpha^{\beta_2+1}) \tag{21}$$

and β_1 and β_2 are given by (9) and (10) respectively.

Proof: See Appendix B.

In Equations (15) and (16) 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 equation (56), 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 (17) 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:

$$A_1^{CCGT} = A^{VRE}(1-\alpha^{\beta_1+1}) \quad (22)$$
$$A_2^{CCGT} = -A^{VRE}\alpha^{\beta_1+1} \quad (23)$$
$$B_2^{CCGT} = B^{VRE} \quad (24)$$
$$B_3^{CCGT} = B^{VRE}(1-\alpha^{\beta_2+1}) \quad (25)$$

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

In Section 5.2 we shall 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. We shall also calibrate the level of the value function V^{CCGT}, and show how it changes depending on the drifts, μ_P and μ_C, and the volatilities σ_P and σ_C.

4.3 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 Equation (3), C_t by Equation (4) and B_t given by:[18]

$$\frac{dB_t}{B_t} = \mu_B B_t dt + \sigma_B B_t dW_t^B \quad \text{with } B_0 = B \quad (26)$$

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

[18] 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 $E(dW_t^B, dW_t^C) = 0.$

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 (Figure 3) are represented the operating profits for such a technology.

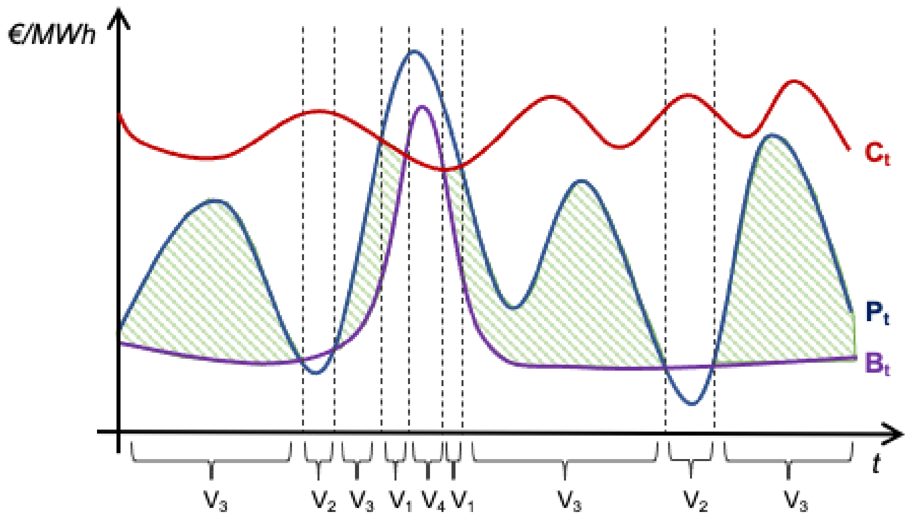

Figure 3: The green area represent the operating profits for a firm capacity supplied by a Coal power plant under the existence of the CRM. The x-axis corresponds to time t, the y-axis are Euro/MWh. The red line represents the marginal costs of the marginal technology, C_t; the blue line represents the day-ahead electricity prices P_t; the cost of generating power from the coal plant, B_t, has its own specific stochastic path. The grey dashed lines identify the four regimes of the value function as described by equation (30).

The instantaneous operating profits from the investment in this model is:

$$\pi_t^{COAL} = \max[\min(P_t - B_t,\ C_t - B_t), 0] \tag{27}$$

or, more specifically:

$$\pi_t^{COAL} = \begin{cases} C_t - B_t & \text{if } \ P_t - B_t \geq C_t - B_t \\ P_t - B_t & \text{if } \ P_t - B_t < C_t - B_t \\ 0 & \text{if } \ \min(P_t - B_t,\ C_t - B_t) < 0 \end{cases} \tag{28}$$

The expected value of the future discounted operating profits is:

$$V^{COAL}(P,C,B) = E_0\left[\int_0^{\infty} \max[\min(P_t - B_t,\ C_t - B_t), 0]e^{-rt}dt\right] \tag{29}$$

Note that when $B_t = 0$, the problem becomes equals to (5) due to the absorbing nature of zero for the process B_t. Then, here we solve (29) 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 (29). The following Proposition summarizes the solution:

Proposition 3. *The NPV of the investment in a Coal power plant can be approximated by:*

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

with

$$V^{COAL}(P,C,B) = \begin{cases} V_1^{COAL}(P,C,B) & \text{if } P \geq C > B \\ V_2^{COAL}(C,B) & \text{if } B \geq C \text{ and } (C-B) < (P-B) \\ V_3^{COAL}(P,C,B) & \text{if } C > P > B \\ V_4^{COAL}(P,B) & \text{if } B \geq P \text{ and } (P-B) < (C-B) \end{cases} \tag{30}$$

and

$$V_1^{COAL}(P,C,B) = \frac{C}{r-\mu_c} - \frac{B}{r} + A_{11}^{COAL}P^{-\eta_1}B^{\eta_1+1} + A_{12}^{COAL}P^{-\eta_1}C^{1+\eta_1} + A_{21}^{COAL}C^{1+\eta_2}B^{-\eta_2} \tag{31}$$

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

$$V_3^{COAL}(P,C,B) = \frac{P}{r-\mu_p} - \frac{B}{r} + B_{11}^{COAL}P^{-\eta_1}B^{\eta_1+1} + B_{21}^{COAL}C^{1+\eta_2}B^{-\eta_2} + B_{22}^{COAL}C^{1+\eta_2}P^{-\eta_2} \tag{33}$$

$$V_4^{COAL}(P,B) = B_{31}^{COAL}B + B_{32}^{COAL}P^{-\eta_2}B^{1+\eta_2} \tag{34}$$

Where the constants are:

$$
\begin{aligned}
A_{11}^{COAL} &= -\frac{r+\eta_2\mu_p}{(\eta_2-\eta_1)r(r-\mu_p)}, \quad A_{12}^{COAL} = \frac{r-\mu_c+\eta_2(\mu_p-\mu_c)}{(\eta_2-\eta_1)(r-\mu_p)(r-\mu_c)} && (35)\\
A_{21}^{COAL} &= -\frac{r-(1+\eta_1)\mu_c}{(\eta_2-\eta_1)r(r-\mu_c)} && (36)\\
A_{31}^{COAL} &= -\frac{r-\eta_2\mu_p}{(\eta_2-\eta_1)r(r-\mu_p)}, \quad A_{32}^{COAL} = \frac{(1-\eta_1)\mu_p}{(\eta_2-\eta_1)r(r-\mu_p)} && (37)\\
B_{11}^{COAL} &= -\frac{r+\eta_2\mu_p}{(\eta_2-\eta_1)r(r-\mu_p)} && (38)\\
B_{21}^{COAL} &= -\frac{r-(1+\eta_1)\mu_c}{(\eta_2-\eta_1)r(r-\mu_c)}, \quad B_{22}^{COAL} = \frac{r-\mu_c+\eta_1(\mu_p-\mu_c)}{(\eta_2-\eta_1)(r-\mu_p)(r-\mu_c)} && (39)\\
B_{31}^{COAL} &= -\frac{r-(1+\eta_1)\mu_c}{(\eta_2-\eta_1)r(r-\mu_c)}, \quad B_{32}^{COAL} = -\frac{\eta_1\mu_c}{(\eta_2-\eta_1)r(r-\mu_c)} && (40)
\end{aligned}
$$

and

$$
\begin{aligned}
\eta_1 &= -\left(\frac{1}{2}+\frac{\mu_c-\mu_p}{\sigma_c^2+\sigma_p^2}\right)+\sqrt{\left(\frac{1}{2}+\frac{\mu_c-\mu_p}{\sigma_c^2+\sigma_p^2}\right)^2+\frac{2(r-\mu_c)}{\sigma_c^2+\sigma_p^2}} > 0\\
\eta_2 &= -\left(\frac{1}{2}+\frac{\mu_c-\mu_p}{\sigma_c^2+\sigma_p^2}\right)-\sqrt{\left(\frac{1}{2}+\frac{\mu_c-\mu_p}{\sigma_c^2+\sigma_p^2}\right)^2+\frac{2(r-\mu_c)}{\sigma_c^2+\sigma_p^2}} < 0
\end{aligned}
$$

with

$$
\begin{aligned}
\mu_p &= \mu_P-\mu_B+\frac{1}{2}\sigma_B^2 && (41)\\
\sigma_p &= \sigma_P-\sigma_B && (42)\\
\mu_c &= \mu_C-\mu_B+\frac{1}{2}\sigma_B^2 && (43)\\
\sigma_c &= \sigma_C-\sigma_B && (44)
\end{aligned}
$$

Proof: See Appendix C

Though the model is more complicate, it is worth to note the symmetry with Model 1. That is, if $B=0$ the model collapses to M1, 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, $V_2^{COAL}(C,B)=A_{31}^{COAL}B+A_{32}^{COAL}C^{1+\eta_1}B^{-\eta_1}$ and $V_4^{COAL}(P,B)=B_{31}^{COAL}B+B_{32}^{COAL}P^{-\eta_2}B^{1+\eta_2}$ represents 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, $V_1^{COAL}(C,B)$ and $V_3^{COAL}(C,B)$ 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.

In section 5.3 we discuss the signs of these constants. We shall also provide the net present value of the investment. Moreover, since Model 3 is the one that encompasses the other two models as special cases, we shall also evaluate each of the four possible regimes, assuming different possible values for the power price, the price cap and the level of the cost. Finally, we conduct some sensitivity analyses to show how the value of the plant changes in relation to μ_B and σ_B in all four regimes.

5 Data and results

5.1 Empirical data and parameters estimation

We start by calibrating the models to real data, using data of the Italian power prices and costs. In particular, we take the Italian wholesale single national power price - PUN (Prezzo Unico Nazionale - in Italian) [19] from 2009 to 2019 as a proxy for the dynamics of P_t; the Natural Gas TTF Spot Price[20] from 2008 to 2019 for C_t; the COAL API2 Futures [21] from 2015 to 2019 for B_t. All three time series have been analysed following the same procedure and considering monthly average prices.[22] First, we test whether the monthly averages of the three time series considered follow a Geometric Brownian Motion (GBM) by adopting a Dickey Fuller (DF) unit root test. Then, we proceed by estimating the trend and uncertainty parameters, μ and σ. [23]

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

[20]Source: Eikon Refinitiv

[21]Source: Investing (`www.investing.com`)

[22]The sample is limited to the end of 2019, excluding the COVID-19 period. and the price turmoils due to the Ukrainian war contingencies.

[23]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.

Both monthly and yearly drift and diffusion terms are computed. Details of the procedure are reported in Appendix D. 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 1.

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

Table 1: Dickey Fuller test results and GBM parameters estimation.

5.2 Model 1 and Model 2 - Numerical results and Sensitivity analysis

In this section we calculate the values for Model 1 and 2. Unless differently stated, we use the figures for the drift and volatility provided above. 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. Table 2 summarises the parameters adopted for the analysis. Note that for current values of price and cost we choose $P = 59.21$ and $C = 19.39$,that correspond to the mean value of the time series of the PUN and the Natural Gas, respectively. Since these prices are hourly (Euro/MWh), in order to calculate figures on a yearly basis they are converted in Euro/MWy by multiplying them by 8760 (the number of hours in one year). In the last two rows of Table 2 we provide the results of calibration of the two models. Note that since $P > C$, we are in the first regime of Equation (6) for Model 1 and Equation (14) for Model 2, respectively.

Note that V_1^{VRE} is higher than V_1^{CCGT}. The main reason is that, differently from Model 1, in Model 2 there are generation costs which decrease the total operating profits of the power plant. Finally, the switching values correspond to $A^{VRE}C^{1+\beta_1}P^{-\beta_1}$ for Model 1 and $A_1^{CCGT}C^{1+\beta_1}P^{-\beta_1}$ for Model 2. We observe that both values are negative.

This is consistent with the fact that they represent the possibility to fall into the regime where revenues are reduced because of a very low price, i.e. a price below the price cap. The next subsection presents a graphical sensitivity analysis, per each model, showing how values change depending on the drift and the volatility parameters.

	Model 1	Model 2	
r	*5*		(%)
P	*59.210 *8760*		(Euro/MWy)
C	*19.386 *8760*		(Euro/MWy)
μ_P	*-0.771*		(%)
μ_C	*-0.599*		(%)
σ_P	*37.37*		(%)
σ_C	*36.75*		(%)
α	-	*50*	(%)
V	1701551	722595	(Euro/MW)
Switching value	-1331600	-793980.5	(Euro/MW)

Table 2: Model 1,2 - parameters adopted and calibration results.

Model 1: VRE coupled with an efficient ESS

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 the equation (7) of A^{VRE} and (8) of B^{VRE}. Consequently, we constraint the range of μ_p and μ_c to $[-0.2, 0.049]$. 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.

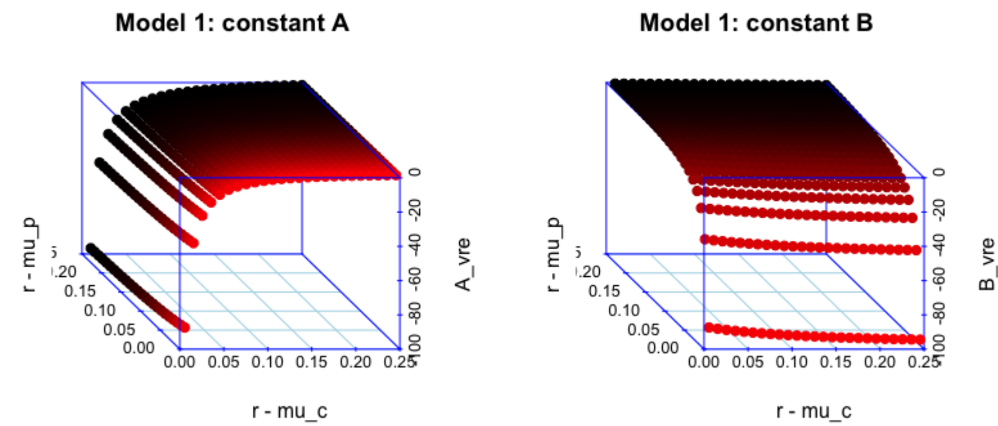

Figure 4: Sensitivity of A^{vre} and B^{vre} with respect to $r - \mu_P$ and $r - \mu_C$.

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 the first regime, where $P > C$.
Both plots in the Figure 5 are based on the analytical equation (6). 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 compensate 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. 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 underlines (the electricity price and the price cap opportunity cost) increases.

Such a result deserves an explanation. Indeed, if we were to look at the investment in a power plant as a real option, namely, the option to gain from the selling electricity in the market, we would expect to see a positive impact of uncertainty on the value of the investment, as for any option. Our analyses shows that the opposite holds true when there is a CRM. Being the latter a price cap on the revenues means that the investor cannot benefit from the price spikes, while still bears the possible falls due to price drops. This explains the negative impact of the uncertainty on the present value of the investment.

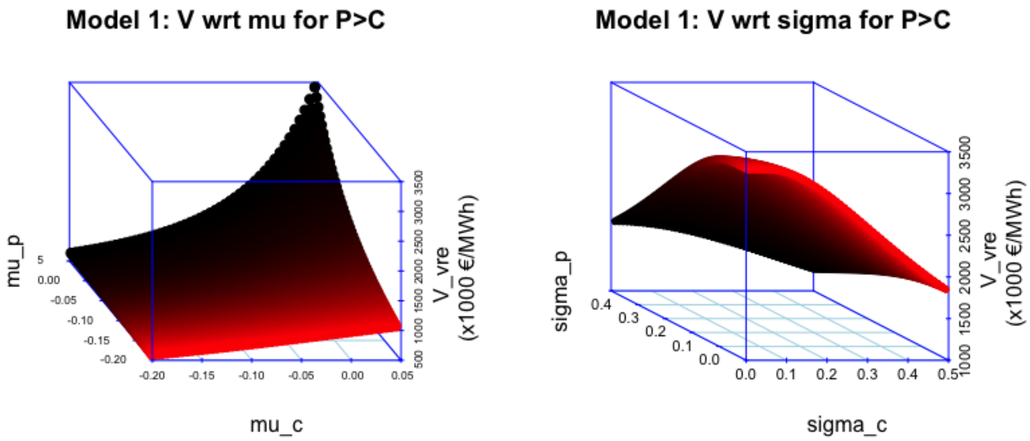

Figure 5: Sensitivity of V^{VRE} with respect to drift and volatility of P and C in the first regime ($P > C$).

Model 2: Efficient CCGT

In this section, looking at the analytical equations of Model 2 given by (18), (19), (20) and (21) 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 that corresponds to the share of C that measures the production costs of the CCGT power plant. The results are presented in Figure 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 start selling again power when the plant is in regime 3. Since in this regime the plant is not earning revenues, the possibility to start again the production has clearly a positive impact on the value. Note that it rises as μ_P and μ_C increase ($r-\mu_P$ and $r-\mu_P$ reduces). A_2^{CCGT} measures 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 measures 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 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 Figure 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.

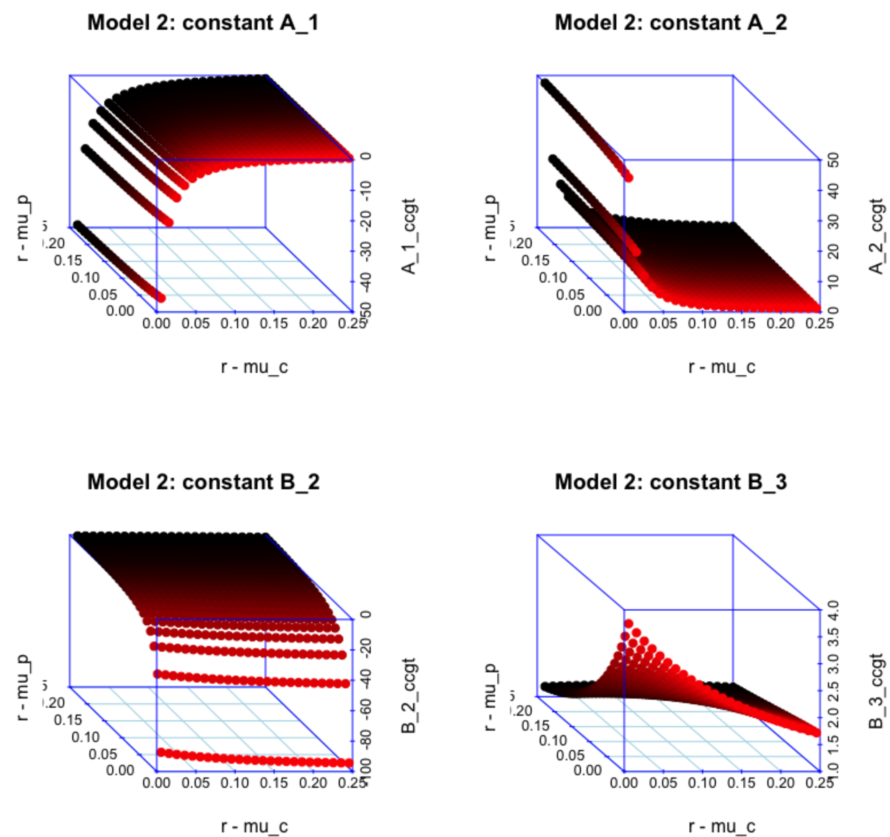

Figure 6: Sensitivity of A_1^{ccgt}, ${}_2^{ccgt}$, B_2^{ccgt} and B_3^{ccgt} with respect to $r - \mu_P$ and $r - \mu_C$

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 Figure 5, that are based on the analytical equation (14), are similar to the ones in Figure 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.

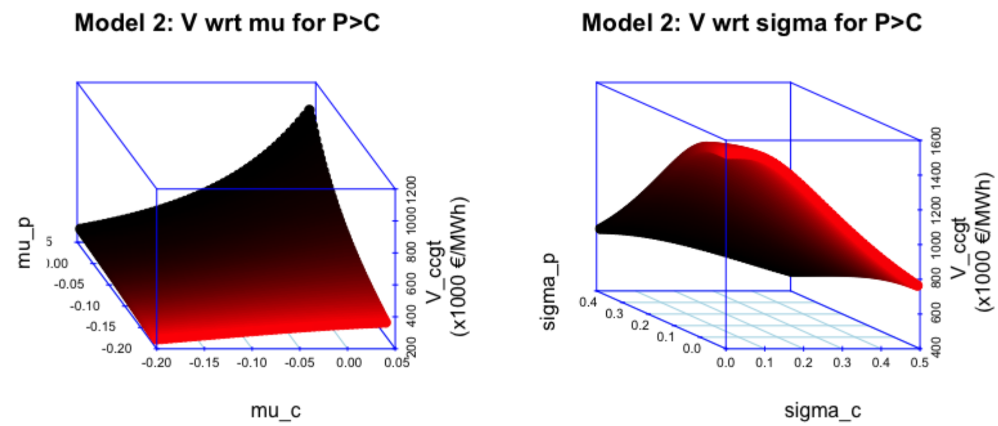

Figure 7: Sensitivity of V^{ccgt} with respect to drift and to volatility parameters of P and C in the 1^{st} regime ($P > C$).

5.3 Model 3 - Numerical results and Sensitivity analysis

In this section we first present the calibration of the value for Model 3, and then the sensitivity analyses. The parameters adopted and the calibrations results are reported in Table 3. We assume that B corresponds to the average price of the entire Coal API2 time series; as before, the value is converted in euro using an average conversion rate (1.097 dollar per euro) and then calculated as Euro/MWy. The drift and volatility terms considered are μ_B^{yearly} and σ_B^{yearly}, respectively. In addition, since Equation (30) is based on the ratio P/C, we have now to consider also μ_p, μ_c, σ_p and σ_c.
The result of calibration is reported in the last box of the Table 3. Since $B \geq C$ and $(C - B) < (P - B)$, we are in the second regime. It is interesting to note that the value V is higher than the ones obtained for Model 1 and Model 2. The reason is that, in the second regime, i.e. $B \geq C$ and $(C - B) < (P - B)$, the power plant is idle since the costs are higher than revenues. It is not convenient for the owner of the plant to generate electricity. Thus the value of the investment in this case is given only by the switching value, or $A_{31}B + A_{32}C^{1+\eta_1}B^{-\eta_1}$, that is, the possibility that in the future the plant will restart selling electricity. This will occur if either the cost will fall or the power price rise (or both); in all cases, this will boost revenues (and since the cost will fall below the price cap, which is set by the gas price, V of coal will be higher).

	Model 3	
r	*5*	(%)
P	*59.210 *8760*	(Euro/MWy)
C	*19.386 *8760*	(Euro/MWy)
B	*70.962 *8760 *1.097*	(Euro/MWy)
μ_P	*-0.771*	(%)
μ_C	*-0.599*	(%)
μ_B	*-0.961*	(%)
μ_p	*1.28*	*(%)*
μ_c	*1.45*	*(%)*
σ_P	*37.37*	*(%)*
σ_C	*36.75*	*(%)*
σ_B	*24.53*	*(%)*
σ_p	*12.84*	*(%)*
σ_c	*12.22*	(%)
V	**8865277**	(Euro/MW)

Table 3: Model 3 - parameters adopted and calibration results.

We calculate now V^{COAL} in all four regimes of the Equation (30). To do so, we change the figures of the calibration accordingly. We highlight that this procedure provides hypothetical yet plausible figures that can be applied to calculate each value. Either 20 Euro/MWh, 40 Euro/MWh, 50 Euro/MWh and 80 Euro/MWh are considered for P, C and B, depending on the specific regime that is being simulated. Table 4 summarizes the value of P, C and B adopted in each regimes, the corresponding figures obtained for V and for the flexibility value[24]. Interestingly enough, see that the value is at its highest value in the second case, and it all accrues from a positive switching value. Even if in the first case the highest electricity price is coupled to the lowest own cost, we see that it does not provide the highest value due to the existence of a negative switching value, namely the possibility to loose operating profits, which reduces the net present value.

[24]Note that μ_B and σ_B are kept fixed to the estimated values adopted before.

	Regime				
	1st	**2nd**	**3rd**	**4th**	
	$P \geq C > B$	$B \geq C$ and $(C - B) < (P - B)$	$C > P > B$	$B \geq P$ and $(P - B) < (C - B)$	
P	80 *8760	80 *8760	40 *8760	40 *8760	(Euro/MWy)
C	50 *8760	50 *8760	50 *8760	50 *8760	(Euro/MWy)
B	20 *8760	60 *8760	20 *8760	60 *8760	(euro/MWy)
V	6723278	6867637	4289901	2462382	(Euro/MW)
Switching value	-2106109	6867637	-1617231	2462382	(Euro/MW)

Table 4: Model 3 - P, C and B values adopted in each regimes and calibration results.

Now we conduct some sensitivity analyses to show how the value change in relation to μ_B and σ_B in all four regimes. We constraint $r > \mu_p$ and $r > \mu_c$ by fix a range on variability for μ_B between -0.01 to 0.3 and for σ_B between 0.01 to 0.05 Results are displayed in Figure 8.

Let us start from the plots of regime 1 and regime 3 (i.e. the two regimes in which power plant is producing). See that V^{COAL} rises as the volatility increases, while it is negatively correlated with the drift term. For the volatility, this is due to the fact that the switching value is negative; as σ_B rises, σ_p and σ_c reduces and thus the negative impact of the switching value reduces too. About the drift term, as the drift rise the impact of the cost on the operating profits is higher, and this obviously reduces the value.

Let us consider now the plots of regime 2 and 4, that correspond to the two regimes in which power plant is shut down. We know that in each of these two regimes the value (V) is positive, as it represents a call option to enter in the market and restart the production. So the effect of a decrease of σ_p and σ_c due to an increase of σ_B should be negative as well as an increase of μ_B. On the basis of this, we observe that in regime 2 such a negative effect can be counterbalanced by the positive effect on μ_p and μ_c, when σ_B is not big enough. On the contrary, in regime 4 the negative effect of an increase in σ_B is not fully counterbalanced by the positive effect of σ_B on μp and μc.

In addition, it should be noted that in all plots the Value tends to stabilize asymptotically around a given value (negative for the first, second and third regime). Therefore, positive effects of σ_B are higher for low values of μ_B.

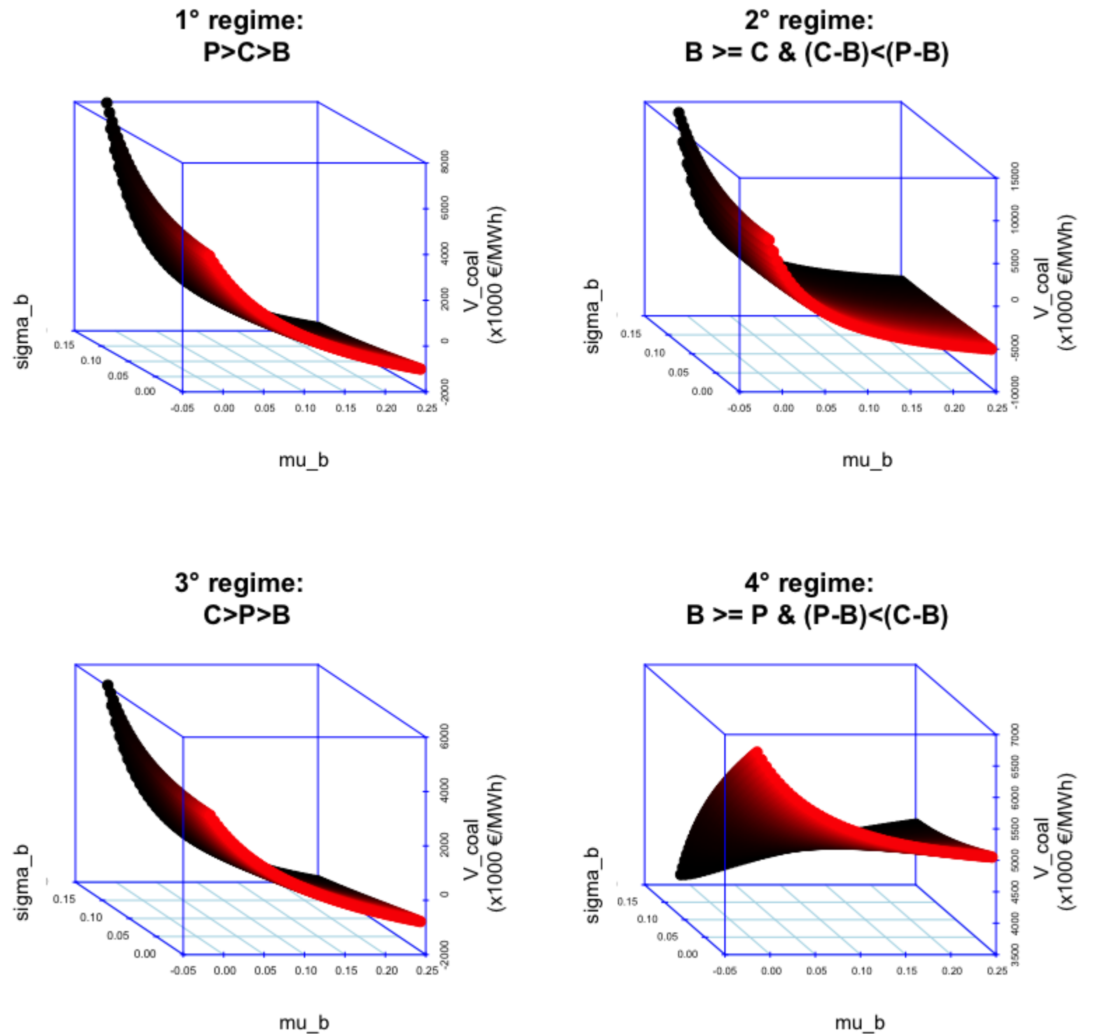

Figure 8: How the value function V^{coal} of Model 3 change in relation to the variations of μ_b and σ_b in the four regimes.

5.4 The social value of the investment

We conclude by measuring the value of the investment from the point of view of the whole society by means of a total welfare function. This allows also ranking the investment induced by the CRM in terms of how compatible they are with the energy transition perspective. Recall that the energy transition requires capacity that reduces greenhouse gas emissions. It is possible to rank the emission across the three considered technologies as $0 = E^{VRE} < E^{GAS} < E^{COAL}$, considering the average emission factors of power production form coal, gas and assuming that VRE do not emit greenhouse gases. At the same time, we know that investment costs differ across technologies, and can be ranked as $I^{M1} > I^{M2} > I^{M3}$. By considering the social cost of the emission, it is possible to translate the emission of each technology into a cost of the emission $\xi(E^i), i = VRE, CCGT, COAL$, and relate this with the cost and the value of the investments in a total welfare function:

$$W^i = \left[-I^i + K + V^i(\cdot) - \xi(E^i)\right],\ i = VRE, CCGT, COAL$$

Clearly, different figures for costs (generation and social costs of carbon) and prices provide different ranking. In what follows, we calculate the total welfare for each technology, assuming the expected net present values derived for each model from the calibration analyses presented above, displayed in Table 2 and 3. For K, we assume a value of 1,125,000 $Euro/MW$, which corresponds to the value of the CRM awarded to new capacity in the Italian Reliability Option auction held in 2019. Fixed investments costs can have a large variability. We assume the values presented in Bersani et al. (2022), using in-shore wind power as a reference for the VRE (1,750,000 Euro/MW). For the storage part of the investment in VRE we assume a value of 2,500,000 Euro/MW (Source: Minkea and Tureka (2018); Poli et al. (2021)). While for gas and coal power plant we assume a value of 1,000,000 Euro/MW and 2,000,000 Euro/MW, respectively (Bersani et al. (2022)). The 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 values by means of a price per unit of emission which measures the social cost of carbon. Its calculation is a complex activity, based on simulating future paths starting from some integrated assessment model which dynamically replicates the structure of an economy. The results, depend, *ceteris paribus*, on assumptions about parameters' weighting, uncertainty, risk aversion and discount and time preferences. As a consequence, the results provide extremely different figures. Discussing all models and corresponding evaluations goes beyond the scope of this paper [25]. We consider here a commonly used reference, namely, the DICE model by Nordhaus (2017), who provides an estimate of 33.87$ per ton of CO_2 for the year 2018[26]. The results of the calculations for the social cost of carbon provides the following figures (Euro/MW): $\xi^{CCGT} = 1969017$, $\xi^{COAL} = 4849716$. The total welfare values are displayed in Table 5.

W^{VRE}	W^{CCGT}	W^{COAL}	
-1423449	-1121422	3140561	(Euro/MW)

Table 5: Total welfare for Model 1, 2 and 3.

[25] For a compact review see Zhang 2021 Zhang et al. (2021).

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

It is interesting to see that with the assumed level of social cost of carbon, the CRM induces a ranking in the investments such that the power generation form coal provides the highest value, followed form gas and VRE. In other words, the ranking is the opposite of the one that the energy transition would require. The reason is due to the low cost of carbon, the high cost of investment in the VRE, and the high Net Present Value of the investment in Coal that overtakes the one in Gas. The latter, ceteris paribus, depends also on the fact that we are in regime 2 of Model 3, i.e., the Value of the investment depend fully on the option value to restart production provided by the investment in the coal baseload.[27] Reducing the investment cost in VRE would not be enough to invert the ranking. For instance, a value of 1076551 $Euro/MW$ for the cost of storage would provide, under the assumed figures for the other costs and prices, a null welfare value for the VRE: $W^{VRE} = 0$ but the total welfare would still imply that the society should choose to invest in coal production (and even more the private investor, should not be called to pay for the social cost of carbon, i. e., looking just at the private value of the investment). see that the total welfare from the investment in gas yields a negative value. This is due to both the cost of emissions, and the low value of the investment in the gas power plant. The latter, in turn, depends on the high negative switching value. Recall that the latter measures the loss in the expected net present value due to the existence of the rigidity and the possibility of losses (or better of lower revenues) induced by the CRM. If one neglects such a value, for instance by looking just at the expected book value of the investment (expected operating profits plus capacity premium net of fixed operating costs), without taking into account the value of the loss of flexibility due to the CRM, would obtain a higher value of the investment (with the figures used here, it would be roughly null). Thus, the rigidity due to the CRM is crucial to make explicit the negative social value of incentivizing the investment in gas-fired power plants through a CRM. In order to induce the CRM to provide a ranking of the investment that favour VRE, it would be necessary to both reduce the cost of investment in this source and increase the carbon cost. For instance, with a storage cost of 1076551 $Euro/MW$ a price of 51 $Euro/tCO_2$ would induce a switching of the ranking in favour of the VRE. The graph below provides a graphical representation of the social value of VRE and of COAL, for different levels of the cost of carbon, and investment costs in VRE. We can immediately see that the lower the investment cost for VRE the lower the carbon price for which the investment in VRE is to be preferred.

[27] Interestingly enough, we note that at the time of the writing of this article, the natural gas price spike coupled with difficulties in gas power supply from Russia have induced several European countries, including Italy, to restart production from coal power plants that were kept idle. Even if the reality is clearly more complex than a theoretical model, we take such an evidence as an indirect confirm of what we show in the text.

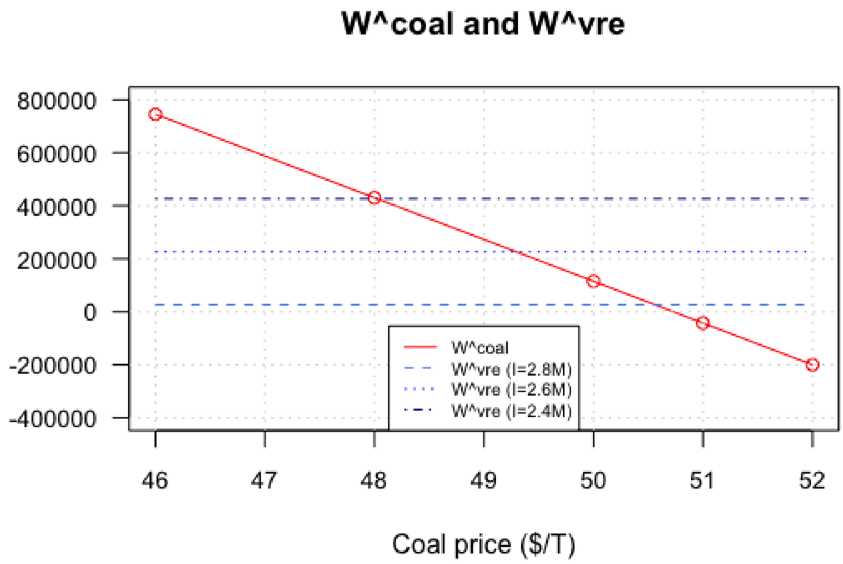

Figure 9: Social value W^{VRE} and W^{COAL} for different levels of the cost of carbon and investment costs in VRE.

6 Conclusions

The aim of this paper was to investigate the value of investments in capacity financed by a Capacity Remuneration Mechanism (CRM), 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. So the Net Present Value of a technology under a CRM is accounted by its investment costs, a capacity premium and its Value function.

In order to discriminate between capacity that favors energy transition and capacity that hinders the technological evolution, we developed three analytical models to study the Value of three different technologies: a capacity provided by Variable Renewable Energy (VRE) source coupled an efficient Energy Storage System (Model 1); a thermal efficient capacity that at the time of the investment is more efficient than the marginal power plant (Model 2) and a brown capacity (Model 3). These technologies have different revenue functions and different underlying stochastic variables to consider. In particular, their Value function depends on the evolution of electricity prices, on the marginal cost of the marginal technology and generation costs, that are uncertain. The three analytical models developed therefore have an increasing level of complexity, from the simplest scheme of the VRE technology with two underlying stochastic variables (i.e. electricity prices and marginal cost of the marginal technology) to the most complex one with three stochastic variables (i.e. electricity prices, marginal cost of the marginal technology and generation costs). For all three models, the Value function is composed by different regimes that depend on the level of the variables considered.

In the last part of this work we performed models calibration and sensitivity analysis. Results show that the presence of CRM shrink power plants revenues and as consequence decrease the final Present Value in all three models considered. In our study we refer to this as the price cap effect value and it is driven by the constants value.

In particular, the sensitivity analysis of Model 1 constants showed that they are always negative in all regimes. In Model 2 instead the constant sensitivity varies in relation to the regime considered. In the first regime, that correspond to the case in which electricity prices are higher than the marginal cost of the marginal technology, is always negative; in the third regime, that correspond to the case in which costs become so high that the plant is shutted down, is always positive; while the two constants of the second regime display an opposite sign.

Also, calibrations of Model 1 and 2 showed that the price cap effect value has a negative impact on final Value. However, the Value resulting by calibrations of Model 1 is higher than that of Model 2. This is probably due to the presence of generation costs in Model 2 that compress the revenues of the plant and consequently its Value. In addition, the sensitivity of Value for Model 1 and 2 displayed a similar behavior: they are positive correlated with drifts of the electricity prices and the marginal cost of the marginal technology while are negative correlated with their volatility terms.

For Model 3 another approach was adopted as, differently from the other two models, it has also stochastic generation costs. The Value in this case is composed of four different regimes: two in which power plant is producing (first and third regime) and the other two where it is idle due to too high generation costs (second and fourth regime). We studied the sensitivity of Value in relation to the drift and volatility terms of generation costs in all four regimes. Results show that the first and third regime have a similar path: they are positively correlated with the volatility while are negatively correlated with the drift term. Instead, in the second and fourth regime different behavior emerged that depends on the magnitude and impact of input parameters, and in particular of the electricity prices and marginal cost of the marginal technology drift and volatility terms. Also, the calibrations of Model 3 showed that the price cap effect has a negative value and decreases the final Value.

Finally, the value of the investment from the point of view of the whole society by means of a total welfare function was provided. Results show that the ranking of three technologies considered is the opposite of the one that the energy transition would desire. In order to induce the CRM to provide a ranking of the investment that favours energy transition, it would be necessary to both reduce investment costs in VRE and increase carbon emission costs.

In our study we adopted Italian data for electricity prices and CRM ex-ante awards in order to produce numerical results. This choice was driven by the fact that we desired to study a market in which capacity remuneration is already in place.[28] Anyway, our results can be applied to different markets providing different investment and social values.

Acknowledgement

An early, preliminary version of this article was presented at the Research dialogues on the complexity of the energy transition workshop in Brescia, December 2021. We thank Sergio Vergalli, Peter Kort and participants to the workshop for their useful comments. Cinzia Bonaldo wishes to thank Anna Creti for the hospitality at the Climate Economics Chair - Paris Dauphine University - and her support and valuable advice received during the four-month visiting period. We thank Massimo Guarnieri, Nicola Poli and Andrea Trovò for their useful discussions and data support about the Long Duration Energy Storage technologies within the project "Grid-optimized vanadium flow batteries: architecture, interconnection and economic factors" (GUAR_RICERCALASCITOLEVI 20_01), funded by the 2019 Research Program of the Interdepartmental Centre Giorgio Levi Cases for Energy Economics and Technology of University of Padova. Clearly, authors remain fully responsible for the content of this paper.

Appendixes

A - Poof of Proposition 1

Defining by $V^2(P,C)$ the value of the investment in the region where $P < C$, i.e., whenever the price cap effect is not binding, it must satisfy the following Bellman equation:

$$rV^2(P,C) = P + \frac{E_t(dV^2(P,C))}{dt}, \text{ for } P < C \tag{45}$$

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

[28]Nevertheless, recently Terna - the Italian TSO - has launched two big capacity auctions, i.e. in November 2019 and in Febrarury 2022. In particular, the 06/11/2019 Terna launched the first capacity auction for the capacity deliver in 2022 for the italian market. Then, the 21/02/2022 Terna opened the second capacity auction for the capacity deliver in 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 .

arbitrage condition can be written as the Bellman equation:

$$rV^2(P,C) = P + \mu_P P V_P^2 + \frac{1}{2}\sigma_P^2 P^2 V_{PP}^2 + \mu_C C V_C^2 + \frac{1}{2}\sigma_C^2 C^2 V_{CC}^2 \tag{46}$$

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. (46) 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 equation (46) as:

$$\begin{aligned}(r-\mu_C)Cv^2(x) =& P + v_x^2(x)((\sigma_P^2 - \mu_P)Px^2 + (\mu_C + \sigma_C^2)Cx) \\ &+ \frac{1}{2}\sigma_P^2 P x^3 v_{xx}^2(x) + \frac{1}{2}\sigma_C^2 C x^2 v_{xx}^2(x)\end{aligned} \tag{47}$$

where:

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

Let consider the homogeneous part of (47). Dividing both parts by C we obtain an ordinary differential equation for the unknown function $v^2(x)$:

$$(r-\mu_C)v^2(x) = (\mu_C - \mu_P + \sigma_C^2 + \sigma_P^2)xv_x^2(x) + \frac{1}{2}(\sigma_C^2 + \sigma_P^2)x^2 v_{xx}^2(x) \tag{48}$$

A general solution for (48) is

$$v^2(x) = A_2 x^{\beta_1} + B_2 x^{\beta_2} \tag{49}$$

where:

$$\begin{aligned}\beta_1 &= -\left(\frac{1}{2} + \frac{\mu_C - \mu_P}{\sigma_C^2 + \sigma_P^2}\right) + \sqrt{\left(\frac{1}{2} + \frac{\mu_C - \mu_P}{\sigma_C^2 + \sigma_P^2}\right)^2 + \frac{2(r-\mu_C)}{\sigma_C^2 + \sigma_P^2}} > 0 \\ \beta_2 &= -\left(\frac{1}{2} + \frac{\mu_C - \mu_P}{\sigma_C^2 + \sigma_P^2}\right) - \sqrt{\left(\frac{1}{2} + \frac{\mu_C - \mu_P}{\sigma_C^2 + \sigma_P^2}\right)^2 + \frac{2(r-\mu_C)}{\sigma_C^2 + \sigma_P^2}} < 0\end{aligned}$$

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

$$\frac{1}{2}(\sigma_C^2+\sigma_P^2)\beta^2+(\mu_C-\mu_P+\frac{1}{2}(\sigma_C^2+\sigma_P^2))\beta-(r-\mu_C)=0 \tag{50}$$

Adding a linear particular solution for (48), the value function $V^2(P,C)$ can thus be expressed as:

$$V^2(P,C)=\frac{P}{r-\mu_P}+CA_2x^{\beta_1}+CB_2x^{\beta_2} \quad \text{for } P<C \tag{51}$$

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:

$$\begin{aligned}V^2(P,C)&=\frac{P}{r-\mu_P}+CB_2x^{\beta_2}\\&=\frac{P}{r-\mu_P}+B_2C^{1+\beta_2}P^{-\beta_2}\end{aligned} \tag{52}$$

Let's know 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:

$$rV^1(P,C)=C+\frac{E_t(dV^1(P,C))}{dt} \quad P\geq C \tag{53}$$

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

$$V^1(P,C)=\frac{C}{r-\mu_C}+CA_1x^{\beta_1}+CB_1x^{\beta_2} \quad \text{for } P\geq C \tag{54}$$

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.:

$$\begin{aligned}V^1(P,C)=&\frac{C}{r-\mu_C}+CA_1x^{\beta_1}\\=&\frac{C}{r-\mu_C}+A_1C^{1+\beta_1}P^{-\beta_1}\end{aligned} \tag{55}$$

Summing up, we get:

$$V(P,C) = \begin{cases} V^1(P,C) = \frac{C}{r-\mu_C} + A_1 C^{1+\beta_1} P^{-\beta_1} & \text{for } P \geq C \\ V^2(P,C) = \frac{P}{r-\mu_P} + B_2 C^{1+\beta_2} P^{-\beta_2} & \text{for } P < C \end{cases} \tag{56}$$

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 and B_2 by imposing the Value Matching (VM) and the Smooth Pasting (SP) conditions:

$$\frac{P}{r-\mu_P} + B_2 C^{1+\beta_2} P^{-\beta_2} = \frac{C}{r-\mu_C} + A_1 C^{1+\beta_1} P^{-\beta_1}$$

$$\frac{1}{r-\mu_P} - \beta_2 B_2 C^{1+\beta_2} P^{-\beta_2-1} = -\beta_1 A_1 C^{1+\beta_1} P^{-\beta_1-1}$$

$$(1+\beta_2) B_2 C^{\beta_2} P^{-\beta_2} = \frac{1}{r-\mu_C} + (1+\beta_1) A_1 C^{\beta_1} P^{-\beta_1}$$

Solving the system we obtain:

$$A_1 = \frac{(r-\mu_C) + \beta_2(\mu_P - \mu_C)}{(\beta_2 - \beta_1)(r-\mu_P)(r-\mu_C)} \tag{57}$$

$$B_2 = \frac{(\mu_P - \mu_C)\beta_1 + (r-\mu_C)}{(\beta_2 - \beta_1)(r-\mu_P)(r-\mu_C)} \tag{58}$$

where

$$\beta_2 - \beta_1 = -\sqrt{\left(\frac{1}{2} + \frac{\mu_C - \mu_P}{\sigma_C^2 + \sigma_P^2}\right)^2 + \frac{2(r-\mu_C)}{\sigma_C^2 + \sigma_P^2}} < 0$$

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

B - Proof of Proposition 2

Following the same procedure as in the proof of Proposition 1, we are able to show that:

$$V^{CCGT}(P,C) = \begin{cases} V_1^{CCGT}(P,C) & = \frac{(1-\alpha)C}{r-\mu_C} + A_1 C^{1+\beta_1} P^{-\beta_1} \text{for } P_t \geq C_t \\ V_2^{CCGT}(P,C) & = \frac{P}{r-\mu_P} - \frac{\alpha C}{r-\mu_C} + A_2 C^{1+\beta_1} P^{-\beta_1} + B_2 C^{1+\beta_2} P^{-\beta_2} \\ & \quad \text{for } \alpha C_t < P_t < C_t \\ V_3^{CCGT}(P,C) & = B_3 C^{1+\beta_2} P^{-\beta_2} \quad \text{for } P_t < \alpha C_t \end{cases} \tag{59}$$

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 condition and the smooth pasting condition between first and second regime in $\frac{C}{P} = 1$. 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 condition and the smooth pasting condition between the first and the third regime in $\frac{C}{P} = \frac{1}{\alpha}$. 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 4 equations in 4 unknown. The solution gives:

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

Solving the system we obtain:

$$A_1 = \frac{(\mu_P-\mu_C)\beta_2 + (r-\mu_C)}{(\beta_2-\beta_1)(r-\mu_P)(r-\mu_C)}(1-\alpha^{\beta_1+1}) \tag{60}$$

$$A_2 = -\frac{\beta_2(\mu_P-\mu_C) + (r-\mu_C)}{(\beta_2-\beta_1)(r-\mu_P)(r-\mu_C)}\alpha^{\beta_1+1} \tag{61}$$

$$B_2 = \frac{(\mu_P-\mu_C)\beta_1 + (r-\mu_C)}{(\beta_2-\beta_1)(r-\mu_P)(r-\mu_C)} \tag{62}$$

$$B_3 = \frac{(\mu_P-\mu_C)\beta_1 + (r-\mu_C)}{(\beta_2-\beta_1)(r-\mu_P)(r-\mu_C)}(1-\alpha^{\beta_2+1}) \tag{63}$$

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.

C - Proof of Proposition 3

Dividing (29) by B, the two-dimensional value of (29) is :

$$v(p,c) = E_0\left[\int_0^{\infty} \max[\min(p_t-1,\ c_t-1),0]e^{-rt}dt\right] \tag{64}$$

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

$$\frac{dp}{p} = \mu_p dt + \sigma_p dW_t^p \quad \text{with } p_0 = p \tag{65}$$

$$\frac{dc}{c} = \mu_c dt + \sigma_c dW_t^c \quad \text{with } c_0 = c \tag{66}$$

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 (64) plays the role of a running cost, the value $v(p,c)$ is given by a couple of optimal timing problem as:

$$v^{op,M3}(p,c) = \max_{\tau} E_0\left[\int_0^{\tau} \min(p_t-1,\ c_t-1)e^{-rt}dt + v^{nop,M3}(p_\tau,c_\tau)e^{-r\tau}\right] \tag{67}$$

$$v^{nop,M3}(p,c) = \max_{\tau} E_0\left[v^{op,M3}(p_\tau,c_\tau)e^{-r\tau}\right] \tag{68}$$

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) Detemple and Kitapbayev (2020b).

Therefore, in order to obtain a close solution for (64), 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:

$$rv^1(p,c) = c - 1 + \mu_p p v_p^1 + \frac{1}{2}\sigma_p^2 p^2 v_{pp}^1 + \mu_c c v_c^1 + \frac{1}{2}\sigma_c^2 c^2 v_{cc}^1 \quad \text{for } p \geq c > 1 \tag{69}$$

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

$$rv^3(p,c) = p - 1 + \mu_p p v_p^2 + \frac{1}{2}\sigma_p^2 p^2 v_{pp}^2 + \mu_c c v_c^2 + \frac{1}{2}\sigma_c^2 c^2 v_{cc}^2 \quad \text{for } c > p > 1 \tag{70}$$

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:

$$rv^2(p,c) = \mu_p p v_p^4 + \frac{1}{2}\sigma_p^2 p^2 v_{pp}^4 + \mu_c c v_c^4 + \frac{1}{2}\sigma_c^2 c^2 v_{cc}^4 \quad \text{for} \;\; c \leq 1 \text{ for all } p \in (0, \infty) \tag{71}$$

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:

$$rv^4(p,c) = \mu_p p v_p^3 + \frac{1}{2}\sigma_p^2 p^2 v_{pp}^3 + \mu_c c v_c^3 + \frac{1}{2}\sigma_c^2 c^2 v_{cc}^3 \quad \text{for} \;\; p \leq 1 \text{ for all } c \in (0, \infty) \tag{72}$$

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:

$$v^1(p,c) = \frac{c}{r - \mu_c} - \frac{1}{r} + \hat{A}_1 c^{1+\eta_1} p^{-\eta_1} + \hat{A}_2 c^{1+\eta_2} p^{-\eta_2} \;\; \text{for } p \geq c > 1 \tag{73}$$

and

$$v^2(p,c) = \hat{A}_3 c^{1+\eta_1} p^{-\eta_1} \;\; \text{for } c \leq 1 \quad \text{and } p \in (0, \infty) \tag{74}$$

where:

$$\eta_1 = -\left(\frac{1}{2} + \frac{\mu_c - \mu_p}{\sigma_c^2 + \sigma_p^2}\right) + \sqrt{\left(\frac{1}{2} + \frac{\mu_c - \mu_p}{\sigma_c^2 + \sigma_p^2}\right)^2 + \frac{2(r - \mu_c)}{\sigma_c^2 + \sigma_p^2}} > 0 \tag{75}$$

$$\eta_2 = -\left(\frac{1}{2} + \frac{\mu_c - \mu_p}{\sigma_c^2 + \sigma_p^2}\right) - \sqrt{\left(\frac{1}{2} + \frac{\mu_c - \mu_p}{\sigma_c^2 + \sigma_p^2}\right)^2 + \frac{2(r - \mu_c)}{\sigma_c^2 + \sigma_p^2}} < 0 \tag{76}$$

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

$$v^3(p,c) = \frac{p}{r - \mu_p} - \frac{1}{r} + \hat{B}_1 c^{1+\eta_1} p^{-\eta_1} + \hat{B}_2 c^{1+\eta_2} p^{-\eta_2} \;\; \text{for} \;\; c > p > 1 \tag{77}$$

and

$$v^4(p,c) = \hat{B}_3 c^{1+\eta_2} p^{-\eta_2} \;\; \text{for } p \leq 1 \quad \text{and } c \in (0, \infty) \tag{78}$$

To determine the constants we compute the matching value condition and the smooth pasting condition 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:

$$
\begin{aligned}
\hat{A}_1^{COAL} &= A_{11}^{COAL} c^{-1-\eta_1} + A_{12}^{COAL} && (79)\\
&= -\frac{r+\eta_2\mu_p}{(\eta_2-\eta_1)r(r-\mu_p)} c^{-1-\eta_1} + \frac{r-\mu_p-(1+\eta_2)(\mu_c-\mu_p)}{(\eta_2-\eta_1)(r-\mu_p)(r-\mu_c)} && (80)\\
\hat{A}_2^{COAL} &= A_{21}^{COAL} p^{\eta_2} = -\frac{r-(1+\eta_1)\mu_c}{(\eta_2-\eta_1)r(r-\mu_c)} p^{\eta_2} && (81)\\
\hat{A}_3^{COAL} &= A_{31}^{COAL} c^{-1-\eta_1} p^{\eta_1} + A_{32}^{COAL} p^{\eta_1} && (82)\\
&= -\frac{r-\eta_2\mu_p}{(\eta_2-\eta_1)r(r-\mu_p)} c^{-1-\eta_1} p^{\eta_1} + \frac{r(1+\eta_2)-(1+\eta_1)(r-\mu_p)}{(\eta_2-\eta_1)r(r-\mu_p)} p^{\eta_1} && (83)\\
\hat{B}_1^{COAL} &= B_{11}^{COAL} c^{-1-\eta_1} = -\frac{r+\eta_2\mu_p}{(\eta_2-\eta_1)r(r-\mu_p)} c^{-1-\eta_1} && (84)\\
\hat{B}_2^{COAL} &= B_{21}^{COAL} p^{\eta_2} + B_{22}^{COAL} && (85)\\
&= -\frac{r-(1+\eta_1)\mu_c}{(\eta_2-\eta_1)r(r-\mu_c)} p^{\eta_2} + \frac{r-\mu_p-(1+\eta_1)(\mu_c-\mu_p)}{(\eta_2-\eta_1)(r-\mu_p)(r-\mu_c)} && (86)\\
\hat{B}_3 &= B_{31}^{COAL} p^{\eta_2} c^{-1-\eta_2} + B_{32}^{COAL} c^{-1-\eta_2} && (87)\\
&= -\frac{r-(1+\eta_1)\mu_c}{(\eta_2-\eta_1)r(r-\mu_c)} p^{\eta_2} c^{-1-\eta_2} - \frac{\eta_1\mu_c}{(\eta_2-\eta_1)r(r-\mu_c)} c^{-1-\eta_2} && (88)
\end{aligned}
$$

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

$$
\begin{aligned}
V_1^{COAL}(P,C,B) =& \frac{C}{r-\mu_c} - \frac{B}{r} + A_{11}^{COAL} P^{-\eta_1} B^{\eta_1+1} \\
& + A_{12}^{COAL} P^{-\eta_1} C^{1+\eta_1} + A_{21}^{COAL} C^{1+\eta_2} B^{-\eta_2} \quad \text{for } P-B \geq C-B && (89)\\
V_2^{COAL}(C,B) =& A_{31}^{COAL} B + A_{32}^{COAL} C^{1+\eta_1} B^{-\eta_1} \quad \text{for } C-B \leq 0 \text{ and } \frac{P}{B} \in (0,\infty) && (90)\\
V_3^{COAL}(P,C,B) =& \frac{P}{r-\mu_p} - \frac{B}{r} + B_{11}^{COAL} P^{-\eta_1} B^{\eta_1+1} + B_{21}^{COAL} C^{1+\eta_2} B^{-\eta_2} \\
& + B_{22} C^{1+\eta_2} P^{-\eta_2} \quad \text{for } C-B>P-B && (91)\\
V_4^{COAL}(P,B) =& B_{31}^{COAL} B + B_{32}^{COAL} P^{-\eta_2} B^{1+\eta_2} \quad \text{for } P-B \leq 0 \text{ and } \frac{C}{B} \in (0,\infty) && (92)
\end{aligned}
$$

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,

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

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 Figure 10, 11 and 12 are represented the monthly average prices for PUN, TTF Day-ahead Natural Gas and Coal (API2) Futures, respectively.

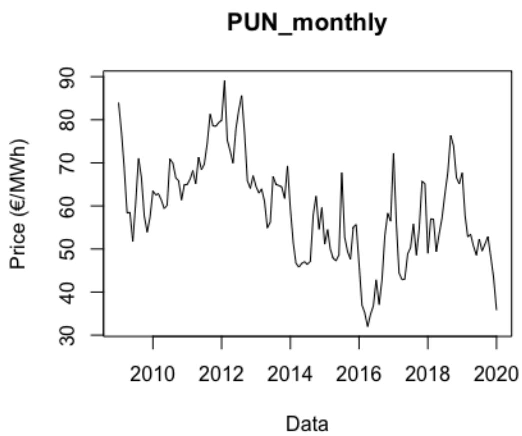

Figure 10: Monthly PUN prices

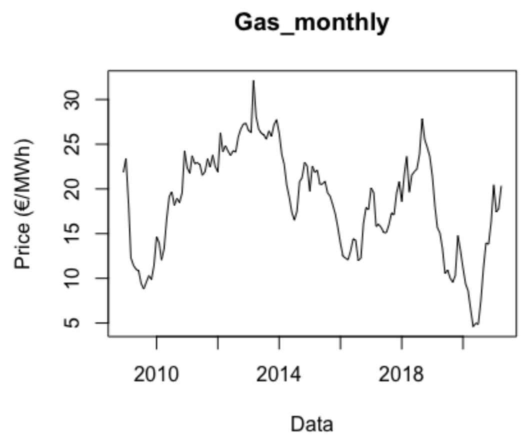

Figure 11: Monthly TTF Gas prices

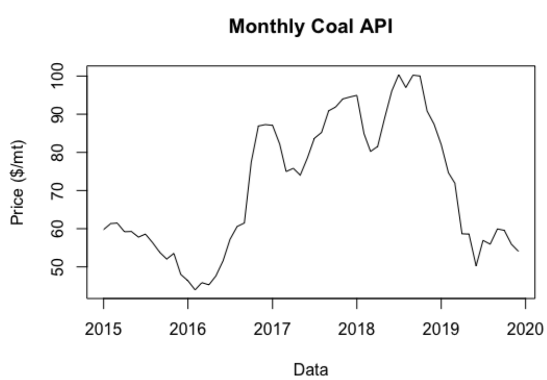

Figure 12: Monthly API2 Futures prices

A Dicky-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 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 Equation 3, 4 and 26 and applying Ito's formula, we can rewrite the three equations as:

$$dlnP_t = \left(\mu_P - \frac{\sigma_P^2}{2}\right) dt + \sigma_P dW_t^P \quad (93)$$

$$dlnC_t = \left(\mu_C - \frac{\sigma_C^2}{2}\right) dt + \sigma_C dW_t^C \quad (94)$$

$$dlnB_t = \left(\mu_B - \frac{\sigma_B^2}{2}\right) dt + \sigma_B dW_t^B \quad (95)$$

Then we can rewrite them as:

$$lnP_t - lnP_{t-1} = a_0 + \delta lnP_{t-1} + e_t \quad (96)$$

$$lnC_t - lnC_{t-1} = b_0 + \delta lnC_{t-1} + z_t \quad (97)$$

$$lnB_t - lnB_{t-1} = c_0 + \delta lnB_{t-1} + k_t \quad (98)$$

The null hypothesis is that lnP_t, lnC_t and lnB_t have a unit root, $H_0 : \delta = 0$, while the alternative hypothesis is $H_1 : \delta < 0$. 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, $-0.938 > -2.58$.

References

Andreis, L., Flora, M., Fontini, F., and Vargiolu, T. (2020). Pricing reliability options under different electricity price regimes. *Energy Economics*, 87:104–705.

Ashokkumar, P. A., Pranav, B., and Darji, B. (2020). Capacity market functioning with renewable capacity integration and global practices. *The Electricity Journal*, 33:106708.

Askeland, M., Jaehnert, S., and Korpas, M. (2017). Equilibrium assessment of storage technologies in a power market with capacity remuneration. *Sustainable Energy Technologies and Assessments*, 31:228–235.

Bersani, A. M., Falbo, P., and L., M. (2022). Is the ets an effective environmental policy? undesired interaction between energy-mix, fuel-switch and electricity prices. *Energy Economics*, 110:105981.

Bhagwat, P., Marcheselli, A., Richstein, J., Chappin, E., and De Vries, L. (2017). An analysis of a forward capacity market with long-term contracts. *Energy Policy*, 31:255–267.

Bonaldo, C., Caporin, M., and Fontini, F. (2022). The relationship between day-ahead and future prices in electricity markets: An empirical analysis on italy, france, germany, and switzerland. *Energy Economics*, 110.

Bonaldo, C. and Poli, N. (2022). Vanadium redox flow batteries: characteristics and economic value. In *Smart Innovation, System and Technologies*.

Borovkova, S. and Schmeck, M. D. (2017). Electricity price modeling with stochastic time change. *Energy Economics*, 63:51–65.

Bowring, J. (2013). Capacity markets in pjm. *Economics of Energy & Environmental Policy*, 2:47–65.

Burger, M., Klar, B., Mueller, A., and Schindlmayr, G. (2004). A spot market model for pricing derivatives in electricity markets. *Quantitative Finance*, 4:109–122.

Caporin, M., Fontini, F., and Segato, S. (2021). Has the eu-ets financed the energy transition of the italian power system? *International Journal of Financial Studies*, 9:1–15.

Caputo, A. (2017). Fattori di emissione atmosferica di co2 e altri gas a effetto serra nel settore elettrico.

Cramton, P., Ockenfels, A., and Stoft, S. (2013). Capacity market fundamentals. *Economics of Energy & Environmental Policy*, 2:28–48.

Creti, A. and Fontini, F. (2019). *Economics of electricity markets, competition and rules*. Cambridge University Press.

Detemple, J. and Kitapbayev, Y. (2020a). The value of green energy: Optimal investment in mutually exclusive projects and operating leverage. *The Review of Financial Studies*, 33:3307–3347.

Detemple, J. and Kitapbayev, Y. (2020b). The value of green energy under regulatory uncertainty. *Energy Economics*, 89.

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

Fu-Wei, H., Shi, C., and Jyh-Horng, L. (2022). Free riding and insurer carbon-linked investment. *Energy Economics*, 107:105838.

Galetovic, A., Munoz, C., and Wolak, F. (2015). Capacity payments in a cost-based wholesale electricity market: The case of chile. *The Electricity Journal*, 28:80–96.

Hancher, L., De Hauteclocquoe, A., and Sadowska, M. (2015). *Capacity Mechanisms in EU Energy Market*. Oxford University Press.

Joskow, P. (2008). Capacity payments in imperfect electricity markets: Need and design. *Utilities Policy*, 16:159–170.

Joskow, P. and Tirole, J. (2007). Reliability and competitive electricity markets. *The Rand Journal of Economics*, 38:60–84.

Joskow, P. and Wolfram, C. (2012). Dynamic pricing of electricity. *The American Economic Review*, 102:381–385.

Khalfallah, M. (2009). Long term capacity adequacy in electricity markets: Reliability contracts vs capacity obligations. *Energy Studies Review*, 16:1–37.

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

Kozlova, M. (2017). Electricity price modeling with stochastic time change. *Renewable and Sustainable Energy Reviews*, 80:180–196.

Lin, J. and Vatani, B. (2017). Impact of capacity market design on power system decarbonization. In *Proceedings of the 2017 14th International Conference on the European Energy Market (EEM)*, pages 6–9, Dresden, Germany.

Mastropietro, P., Fontini, F., Rodilla, P., and Battle, P. (2018). The italian capacity remuneration mechanism: Critical review and open questions. *Energy Policy*, 123:659–669.

Minkea, C. and Tureka, T. (2018). Materials, system designs and modelling approaches in techno-economic assessment of all-vanadium redox flow batteries – a review. *Journal of Power Sources*, 376:66–81.

Neuhoff, K., Diekmann, J., Kunz, F., Ruester, S., Schill, W., and Schwenen, S. (2016). A coordinated strategic reserve to safeguard the european energy transition. *Utilities Policy*, 41:252–263.

Nordhaus, W. (2017). Revisiting the social cost of carbon. *Proceedings of the National Academy of Sciences*, 114:1518–1523.

Ozdemir, O., de Joode, J., Koutstaal, P., and van Hout, M. (2013). Financing investment in new electricity generation capacity: The impact of a german capacity market on northwest europe. In *Proceedings of the 2013 10th International Conference on the European Energy Market (EEM)*, pages 1–8, Stockholm, Sweden.

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

Przemyslaw, K., Komorowska, A., Zamasz, K., Kinelski, G., and Kaminski, J. (2021). Capacity market and (the lack of) new investments: Evidence from poland. *Energies*, 14:7843.

Roques, F. (2008). Market design for generation adequacy: Healing causes rather than symptoms. *Utilities Policy*, 16:171–183.

Sezgen, O., Goldman, C., and Krishnarao, P. (2007). Option value of electricity demand response. *Energy*, 32:108–119.

Spees, K., Newell, S., and Pfeifenberger, J. (2013). Capacity markets. lessons learned from the first decade. *Economics of Energy & Environmental Policy*, 2:13–26.

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

Zhang, H., Jin, G., and Zhang, Z. (2021). Coupling system of carbon emission and social economy: a review. *Technological Forecasting and Social Change*, 167:120730.

FONDAZIONE ENI ENRICO MATTEI WORKING PAPER SERIES
"NOTE DI LAVORO"
Our Working Papers are available on the Internet at the following address:
https://www.feem.it/pubblicazioni/feem-working-papers/

"NOTE DI LAVORO" PUBLISHED IN 2022

1. 2022, Daniele Crotti, Elena Maggi, Evangelia Pantelaki, Urban cycling tourism. How can bikes and public transport ride together for sustainability?
2. 2022, Antonio Acconcia, Sergio Beraldo, Carlo Capuano, Marco Stimolo, Public subsidies and cooperation in research and development. Evidence from the lab
3. 2022, Jia Meng, ZhongXiang Zhang, Corporate Environmental Information Disclosure and Investor Response: Empirical Evidence from China's Capital Market
4. 2022, Mariagrazia D'Angeli, Giovanni Marin, Elena Paglialunga, Climate Change, Armed Conflicts and Resilience
5. 2022, Davide Antonioli, Claudia Ghisetti, Massimiliano Mazzanti, Francesco Nicolli, The economic returns of circular economy practices
6. 2022, Massimiliano Mazzanti, Francesco Nicolli, Stefano Pareglio, Marco Quatrosi, Adoption of Eco and Circular Economy-Innovation in Italy: exploring different firm profiles
7. 2022, Davide Antonioli, Claudia Ghisetti, Stefano Pareglio, Marco Quatrosi, Innovation, Circular economy practices and organisational settings: empirical evidence from Italy
8. 2022, Ilenia Romani, Marzio Galeotti, Alessandro Lanza, Besides promising economic growth, will the Italian NRRP also produce fewer emissions?
9. 2022, Emanuele Ciola, Enrico Turco, Andrea Gurgone, Davide Bazzana, Sergio Vergalli, Francesco Menoncin, Charging the macroeconomy with an energy sector: an agent-based model
10. 2022, Emanuele Millemaci, Alessandra Patti, Nemo propheta in Patria: Empirical Evidence from Italy
11. 2022, Daniele Valenti, Andrea Bastianin, Matteo Manera, A weekly structural VAR model of the US crude oil market
12. 2022, Banchongsan Charoensook, On Efficiency and Stability in Two-way Flow Network with Small Decay: A note
13. 2022, Shu Guo, ZhongXiang Zhang, Green credit policy and total factor productivity: Evidence from Chinese listed companies
14. 2022, Filippo Bontadini, Francesco Vona, Anatomy of Green Specialisation: Evidence from EU Production Data, 1995-2015
15. 2022, Mattia Guerini, Fabio Vanni, Mauro Napoletano, *E pluribus, quaedam*. Gross domestic product out of a dashboard of indicators
16. 2022, Cinzia Bonaldo, Fulvio Fontini, Michele Moretto, The Energy Transition and the Value of Capacity Remuneration Mechanisms

Fondazione Eni Enrico Mattei
Corso Magenta 63, Milano – Italia

Tel. +39 02 403 36934

E-mail: letter@feem.it
www.feem.it

Fondazione Eni Enrico Mattei