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The Economic Sustainability of Variable Renewable Energy Considering the Negotiation of Different Support Schemes

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Abstract: The increase in the prices of fossil fuels and environmental issues are leading to a high investment in wind power and solar photovoltaic all over Europe, reducing its dependence on imported fossil fuels. The European countries started incentive programs for investment in these renewable technologies, which consisted of fixed and market premium feed-in tariffs. These feed-in schemes involve long-term contracts with updated prices over inflation. These incentives highly increase the investment and installation of new renewable capacity in Europe. They lead to high renewable penetrations in power systems but originate a tariff deficit due to the difference between market prices and the tariffs paid to these technologies. End-use consumers pay the tariff deficit on retail tariffs. This work analyzes the market-based remuneration of variable renewable energy considering different support schemes and the role of risk-sharing contracts in mitigating the spot price volatility. It presents models able to negotiate bilateral contracts considering risk management, notably risk attitude and risk sharing, bid establishment, and clause (by-laws) negotiation. Furthermore, to evaluate the economic sustainability of renewable generation in Spain, it presents a study for different 12-year support schemes starting in 2010. The results confirmed that, in the case of using risk-sharing contracts during crisis periods, the incidence of low energy prices (price "cannibalization") decreases, such as the tariff deficit. Furthermore, in the case of high-inflation periods, these contracts hedge against the increase in retail prices, resulting in an economic surplus for consumers.

Keywords: economic sustainability; electricity markets; renewable investments; risk management; support schemes; variable renewable energy; tariff deficit

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Citation: Algarvio, H. The Economic Sustainability of Variable Renewable Energy Considering the Negotiation of Different Support Schemes. *Sustainability* **2023**, *15*, 4471. https://doi.org/10.3390/su15054471

Academic Editors: Yu Hao, Haitao Wu, Muhammad Irfan and Xiaodong Yang

Received: 21 December 2022
Revised: 24 February 2023
Accepted: 27 February 2023
Published: 2 Maech 2023

1. Introduction

The organization of the power sector has changed throughout the last century with the liberalization process that led to the start of competition in both wholesale and retail markets [1]. Four main options exist to purchase and sell electricity [2]: spot, continuous, bilateral, and derivative markets. The first consists of day-ahead, intraday, or real-time electricity pools, where supply-and-demand players place their offers to sell or buy energy [3]. The market operator supervises and mediates negotiations in these auction-based markets. It obtains the spot clearing price by matching the aggregated supply and load curves to maximize participants' social welfare. Sellers that offer energy at a price lower or equal to the market price will be scheduled to deliver it (or part of it in the case of several marginal sellers) and will receive the market clearing price [4]. Market players can participate in the continuous intraday market until 15 min ahead of real-time operation. This market automatically clears opposite bids based on the pay-as-bid scheme [5]. Market participants can also engage in bilateral contracts to fulfill their long-term energy needs. A bilateral contract is an agreement between two parties where one commits to deliver energy and the other pays for it. The advantage of bilateral contracts concerning spot markets is that the terms (such as the quantity of energy, price, and maturity of contract) are custom-made to the parties' needs. Derivatives markets provide the most-used financial instruments. The most common are futures, swaps, forward, and option contracts. Swaps are also known as contracts for differences (CfDs) [6]. These contracts can require the physical delivery of electricity or have a purely financial settlement.

Consumers may have to consume electricity a few seconds after it is generated. Consequently, generation shall match demand to ensure efficiency, stability, and reliability. Market participants are exposed to several risks since they have to consider energy and price forecasts [7–10]. These include financial risks related to the high volatility of spot prices, which can reach peaks in periods of insufficient generation. Moreover, it is relevant to mention the risks related to net load forecasts because of uncertainty concerning demand and variable renewable energy source (vRES) generation [11]. Risk hedging is essential to market participants, and financial instruments can be used when two parties with opposite positions are willing to exchange risk [12]. Derivative and bilateral markets provide financial instruments that participants can trade bilaterally. Bilateral contracts can also help to hedge against the powerful position of big producers in the spot market by not allowing buyers to be dependent on them to fulfill their energy needs. Another advantage of bilateral support schemes is the economic incentive given to renewable energy source (RES) investments [13], guaranteeing their economic sustainability.

Support schemes can be negotiated using agent-based models. Electricity markets are a complex evolving reality–there is now a growing number of market participants, each one with their own set of objectives, strategies, and exposure to risk [3,4,11,14]. One way to model such a complex system is by using autonomous software agents. They can respond to changes that occur in the environment in a timely fashion, exhibit goal-directed behavior, and interact with other agents to reach their design objectives. Against this background, this paper presents several key features of software agents able to negotiate support schemes, paying special attention to risk management, notably risk attitude, risk sharing, and price negotiation [12]. Furthermore, it presents a study where the Spanish government, as an agent, opens a public contest to negotiate risk-sharing contracts with vRES investors. The results are compared with other support schemes. In addition to feed-in-tariff (FiT) and premium (FIP) schemes already in place, it also considers regulated one-way CfDs [15]. So, the public contest has two phases. In the first phase, investors are invited to submit their proposals to an auction-based pool. The investors who pass to the second phase, being aware of the opponents' offers, are invited to negotiate the strike prices with the government. The government agent proposes small strike prices that guarantee them low but positive returns, being compensated when market prices are higher than strike prices. The goal is to demonstrate a risk-sharing deal between both agents because RES agents only receive high returns if market prices rise, encouraging them to bid higher prices and avoiding the incidence of near-zero spot prices. These support schemes are compared with the two used in Spain, especially concerning the system cost, vRES remunerations, and tariff deficit in 2010 and 2022. Against this background, the main objective of this work is to present and test risk-sharing support schemes to speed up the transition to carbon-neutral societies, guaranteeing the economic sustainability of renewable power plants and lower retail energy prices. The purpose of the paper is fourfold:

1. Adapting a model for the multi-party negotiation of different support schemes;
2. Presenting models of different support schemes;
3. Outlining the equipment of buyer (government) and seller (vRES) agents with concession strategies, trading tactics, and a risk management process;
4. Conducting a study and sensibility analysis to test the above models considering real data of the following: (i) the Spanish traditional support schemes, (ii) Iberian prices, and (iii) the vRES investment, operational, and maintenance costs.

The remainder of this paper is structured as follows. Section 2 presents a literature review. Section 3 introduces bilateral contracts and negotiation models. Section 4 presents support scheme models and RES performance indicators. Section 5 presents a study on the application of different support schemes in Spain. Finally, concluding remarks are presented in Section 6.

2. Literature Review

When global energy policies started considering the environmental impacts of the traditional fossil fuel power plants, introducing the dioxide carbon cost and the renewable energy certificates, they started a policy for incentivizing investment in RES [16–19]. Financing institutions need guarantees of future returns to finance new vRES projects [20–22]. Hence, if investors have long-term forward agreements to sell their energy, they guarantee a stable revenue [23]. Traditionally, FiTs, FiPs, and regulated one-way CfDs are the most-used support schemes for new RES investments [15,24–26]. FiTs consist of a fixed tariff (updated with inflation) that gives a fixed return per produced energy during a significant period (10–15 years). FiPs consist of a payment computed as the market price of electricity plus a premium. The market premium is similar to FiPs but considers a tariff with up and down boundaries (caps) that guarantee a positive return to investors. Regulated one-way CfDs consider the negotiation of a strike price indexed to spot prices, which corresponds to the minimum remuneration of investors. It is similar to the market premium but without upper bounds [27]. When spot prices are lower than the strike price, investors receive the strike price. Otherwise, they receive the market price. It is similar to financing CfDs but considers variable generation and its physical delivery. These support schemes provide a guaranteed return to investors with a small price risk. The price risk and the imbalance costs are assumed by governments and paid by end-use consumers. Variable RESs (vRESs) have substantial capital costs, near-zero marginal costs, and outputs dependent on weather conditions [28].

Externalities, such as RES incentives, highly increase the investment in RESs, increasing the penetration of these sources in the power grid. However, they led to a tariff deficit due to the high costs of the support schemes paid to investors compared to market prices and also because of the reduction in the working hours of the traditional dispatchable power plants with reserve agreements. This reduction increases the capacity costs that governments pay to traditional generation, which increases the over-cost of the power system [15]. Recently, RES investors have also considered power purchase agreements (PPAs), which are similar to FiTs but used for shorter periods [29]. Considering PPAs, investors hedge against spot price decreases, but the buyers of their energy only partially hedge against spot price increases [28]. A less risky option considers trading risk-sharing contracts (RSCs) indexed to the spot price [12]. In RSCs, the parties negotiate the strike price and the shared risk. When spot prices are below the strike price, sellers have to compensate buyers. Otherwise, buyers compensate sellers. This type of contract may avoid the vRES "cannibalization" of spot prices, such as the incidence of negative spot prices [30,31].

Algarvio et al. [15] studied how considering public contests with two-phase auctions of vRES support schemes may decrease the awarded prices. The first and second phases of the public contest consist of a simple auction and a bilateral negotiation between governments and the participants, respectively. The authors concluded that, by accessing the results of the first phase, the participants could adjust their position to get their projects accepted in the second phase, reducing the awarded prices. Bohland and Schwenen [25] studied the impact of vRES support schemes in the competition and market outcomes of day-ahead markets, considering FiTs and FiPs. The study considered data from the Iberian day-ahead market of electricity (MIBEL). While FiTs give a return independent of market prices, FiPs incentivize vRESs to bid prices higher than marginal prices, mitigating the price "cannibalization" effect of vRESs. They concluded that FIPs increase the markup of vRES, mainly of large-scale units, but decrease competition because the larger units exercise market power. Anatolitis et al. [26] studied how vRESs auction-based support schemes shall be designed to decrease awarded prices by analyzing 220 European auctions. They concluded that sufficient competition is the most important aspect to decrease awarded prices. Auctions shall avoid quotas and restricted realization periods and consider multi-technology and ceiling prices to increase competition. Furthermore, support schemes considering pay-as-bid prices instead of marginal auctions may reduce costs and are fairer by considering the different units' production costs [24].

3. Bilateral Contracts and Negotiation

In derivative and bilateral markets are negotiated standard bilateral contracts to hedge against spot price volatility.

3.1. Standard Bilateral Contracts

Electricity markets present different types of standard contracts to trade electricity: forward, futures, option, and CfDs [12]. Forward contracts imply a commitment between the parties to sell or buy a fixed amount of electricity in a future time for a price. Unlike futures contracts, they involve commitments regarding the date on which the energy and the payment are transacted [14]. Forwards do not consider a financial settlement, but physical delivery is always required. Futures contracts include the commitment to buy or sell a quantity of energy at a future time for an uncertain final price [7]. These contracts may have daily settlements between the agreed price and the variable spot price. The parties do not interact directly, and a central counter-party guarantees the fulfillment of obligations. The physical delivery of futures contracts is optional. Option contracts are similar to futures, but only their sellers must commit to the buyers' decisions on the activated options. By paying an initial fee, buyers have the right to buy (call option) or sell (put option) a specific quantity of electricity at a future time. Financing CfDs involve no physical delivery of energy by sellers. The parties fulfill their energy needs in the spot market during the duration of the contract [27]. They establish a bilateral agreement regarding an amount of (virtual) energy for a fixed price or a set of fixed prices called strike prices. These prices are negotiated for single or multiple periods. In addition, they agree on reference price indexes (e.g., the spot price), which are used to compute the differences to be settled during the delivery period [12]. In the case of a two-way CfD, the seller will pay the difference to the buyer if the reference price is higher than the strike price. Conversely, it is the buyer who pays that difference. In some cases, incentives for investment in new renewable power plants can consider regulated one-way CfDs, where only one of the parties compensates the other [15].

The problem is that these standard contracts are traded based on spot markets and indexed to them. RES investors cannot guarantee their investment return trading on derivatives markets. Against this background, governments incentivize RES investments by proposing support schemes, which consider some of the standard products adapted to RESs. Support schemes facilitate investments in renewable energy technologies whose costs and investment risks cannot be covered by the wholesale market prices.

3.2. Bilateral Negotiation

The presented methodology considers a two-phase public contest to support the investment in new RES power plants. The first phase consists of an auction-based procedure to score proposals. The contest's promoter selects the best proposals for the second phase, which consists of a multi-party bilateral negotiation between the promoter and the selected investors, i.e., during this phase, the promoter starts a bilateral negotiation with each of the selected investors to negotiate the prices of the support schemes. After the end of this phase, the proposal with the highest score wins the contest. The agent-based multi-party negotiation model has been adapted from [32].

The negotiation model is based on automated negotiation (see [7,32–35] for a complete review on negotiation models and tools). The decision to accept or reject an offer depends on multi-issue utility functions, which score offers considering agents' preferences [14,36]. The agents' risk attitudes (preference), λ, can be classified according to the following categories [37]:

1. Risk-averse agents ($\lambda > 0$) who prefer a setting where they have a guaranteed return to another setting where that return can be higher but there is a chance of not getting anything;
2. Risk-seeking agents ($\lambda < 0$) who prefer a setting where there is a chance of making unguaranteed higher returns to another setting where a lower return is guaranteed;

3. Risk-neutral agents ($\lambda = 0$) who only try to maximize profit without considering risk.

To negotiate bilateral contracts considering agents' risk attitudes, a concession strategy, C_f, presented in [27], has been adapted:

$$C_f = C_{fn}\ e^{c\,\lambda} \tag{1}$$

where λ is the value of the agent's risk aversion, C_{fn} is the concession factor of a risk-neutral agent, and $c \in [0;1]$ is a constant that shapes the negotiation behavior of the agent. This constant considers small/high values to decrease/increase the risk attitude influence during negotiation, respectively. Equation (1) represents a family of tactics, one for each pair of values (C_{fn}, c) according to the risk attitude of the agent. Accordingly, several simulations were made to define appropriate values for these parameters. Figure 1 illustrates the behavior of the resulting functions. Analyzing the figure, it can be observed that, for small values of the negotiation behavior, c, agents reduce their attitude towards risk behavior while negotiating. On the contrary, high values of c strengthen the influence of their risk attitude behavior during negotiation.

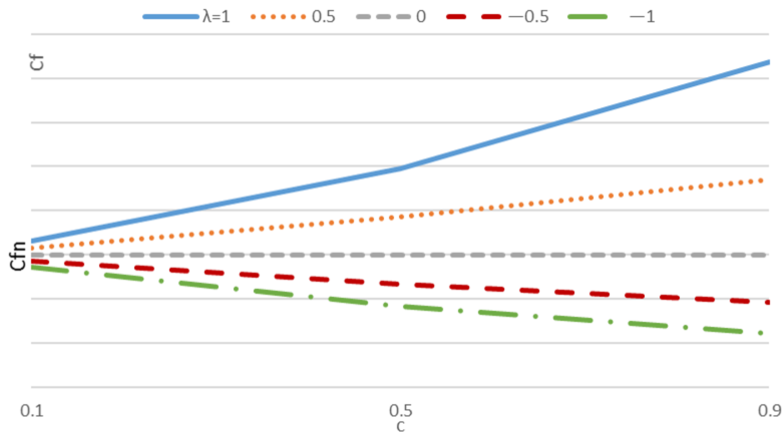

Figure 1. Concession factor for a given measure of risk aversion and negotiation behavior.

4. Support Scheme Models and RES Performance Indicators

To guarantee investment in renewable generation, governments propose different support schemes [24]. This section extends the negotiation model presented in the previous section to simulate typical procedures associated with support schemes. The negotiation of support schemes involves the strike prices and quantities of energy for a generic t-rate tariff, considering different prices per period t.

4.1. Support Schemes

This section presents the main characteristics of the most-used, recent, and prominent support schemes. Typical support schemes may involve only single-period strike prices (one level) updated with inflation and a variable dispatched quantity. Standard products traded on derivative markets consider two levels (off-peak and on-peak prices and quantities) and three levels (off-peak, mid-peak, and on-peak prices and quantities) per day. Non-standard products may consider the private negotiation of more levels backed by legislation, considering hour-wise prices and quantities [12].

FiTs, FiPs, and regulated one-way CfDs are the most-used support schemes to incentivize RES investments [15,24–26]. FiTs are the only support schemes guaranteeing a fixed remuneration for RES investments. These support schemes guarantee a minimum price to investors, hedging them against low market prices. In addition, they protect governments from high market prices, except for regulated one-way CfDs, which compensate investors when market prices are higher than strike prices.

Recently, new RES investments have also considered variable and fixed premiums. Variable premium is the only scheme that guarantees an equal and stable return to all RESs, independent of their productivity and market value. So, it has the drawback of incentivizing the negative or very low price bids of RESs to avoid curtailments. Normally, fixed premiums consider low strike prices, which do not protect investors in the case of low market prices but incentivize them to bid higher prices, avoiding price "cannibalization". If strike prices of fixed premiums and FiTs are similar, they may protect investors in the case of low market prices but do not protect promoters. Under this situation, we can consider that fixed premiums are not well designed because they will have a behavior similar to regulated one-way CfDs. Nevertheless, regulated one-way CfDs and fixed premiums do not hedge against high spot prices and always originate a tariff deficit.

Prominent RSCs used as support schemes may protect both investors and promoters from low and high market prices if well designed [12]. Their strike price and shared risk may consider a negative return to investors in the case of low market prices, to avoid price "cannibalization". Furthermore, closed auction-based public contests do not incentivize competition. Public contests may consider an open auction-based scheme or multi-party negotiation to increase competition. By being aware of the opponents' proposals, investors may reduce their level of aspiration and propose lower strike prices to beat the competition. That is the goal of considering two-phase public contests, which may reduce strike prices in the case of single or multi-party bilateral negotiations [15].

Against this background, Table 1 summarizes the characteristics of the different products used to remunerate RES investors.

Table 1. Characteristics of the different support scheme options and spot products.

Product	Strike/Fixed Price	Boundaries	Negotiation	Low-Price Hedging	High-Price Hedging
FiT	Yes/Yes	No	No	Investor	Both
FiP	Yes/No	Minimum	No	Investor	Both
One-way CfD	Yes/No	Minimum	No	Investor	No
Two-phase CfD	Yes/No	Minimum	Bilateral	Investor	No
RSC	Yes/No	No	No	Both	Both
Two-phase RSC	Yes/No	No	Multi-party	Both	Both
Variable premium	Yes/No	Fixed return	No	Investor	Both
Fixed premium	Yes/No	Minimum	No	Promoter	No
Spot	No/No	No	No	No	No

Mathematical Models

This section presents the formulation of each support scheme used in this work to evaluate their market performance. Accordingly, the agenda includes t energy quantities, i.e., $\{q_1, \ldots, q_t\}$, where each quantity represents the dispatched renewable generation of a specific period t. In particular, CfDs and RSCs require that the parties agree on a set of time-variable, t, strike prices, during period T:

$$Sp = (sp_1, \ldots, sp_t) \tag{2}$$

where the symbols are defined as follows:

(i) Sp is the strike prices' vector;
(ii) $sp_t,\ t = 1, \ldots, T,$ is the strike price of quantity q_t.

CfDs and RSCs also require that the parties agree on a set of reference prices to be used in the definition of the differences. These prices are represented by the following:

$$Rp = (rp_1, \ldots, rp_t) \tag{3}$$

where the symbols are defined as follows:

(i) Rp is the reference prices' vector;
(ii) $rp_t,\ t = 1, \ldots, T,$ is the reference price associated with a specific period or block of a day t.

The multiplication of the differences between prices by energy gives the financial compensation. These vectors can be simplified considering their use in typical support schemes or standard products. The most traditional support schemes considered are FiTs, FiPs, and regulated one-way CfDs [15,24]. FiTs are the most-used support schemes and are similar to two-way CfDs. They considered a fixed strike price, sp_t, per unit of energy with yearly inflation updates during the contract duration. When the market reference price, rp_t, is lower than the strike price, the government (buyer) pays the difference (pay-off). Otherwise, it is the RES (seller) who compensates the government. From the point of view of the RES, the pay-off, $Diff_s$, it has to receive (if positive) or pay (if negative) is as follows:

$$Diff_s = \sum_{t=1}^{T} [sp_t - max(rp_t, 0)] \times q_t \tag{4}$$

The government has to compute exactly the opposite value, being the RES remuneration, Π_s, which equals to the following:

$$\Pi_s = Diff_s + \sum_{t=1}^{T} rp_t \times q_t \tag{5}$$

FiPs are similar to FiTs but consider a fixed premium, fp_t, and a minimum, $minp_t$, and maximum, $maxp_t$, price cap. The sum of the spot price with the fixed premium has to stay between the caps, being the RES remuneration, which equals to the following:

$$\Pi_s = \sum_{t=1}^{T} min[max(fp_t + rp_t, minp_t), maxp_t] \times q_t \tag{6}$$

Regulated one-way CfDs consider that RESs receive the maximum value between the reference spot price and the negotiated strike price. In this case, only RESs are compensated, and the RES remuneration is computed as follows:

$$\Pi_s = \sum_{t=1}^{T} max(rp_t, sp_t) \times q_t \tag{7}$$

Traditional support schemes guarantee the return of RESs but originate the price "cannibalization", negative prices, and a tariff deficit. Price "cannibalization" occurs because vRESs have near-zero marginal costs and support schemes with guaranteed returns. So, they offer near-zero prices at spot markets, which means that they are the first players of the supply merit order, pushing out of the market power plants with higher marginal costs. Historically, high penetrations of vRESs reduce market prices, which leads to price "cannibalization" [15,30,31]. Considering these support schemes, some markets force vRESs to bid the market minimum price cap, guaranteeing they are the first in the merit order. Other markets allow vRESs to bid strategically. Markets with negative price caps and vRESs with support schemes that only remunerate their programmed dispatch may have vRESs bidding negative prices to avoid curtailments in the case of energy excess. In these markets, vRESs prefer to bid strategically and receive lower remunerations rather than non-remunerated curtailments. Support schemes with high guaranteed fixed prices, price "cannibalization", and negative prices increase the tariff deficit, i.e., the difference between spot prices and RES remuneration. The tariff deficit affects the retail tariffs of end-use consumers. So, it may increase their retail tariff, such as the difference between retail and wholesale tariffs. Currently, fixed and variable premiums are used to support investments in RESs. Fixed premiums consist of a fixed remuneration on top of the market price:

$$\Pi_s = \sum_{t=1}^{T} (fp_t + rp_t) \times q_t \tag{8}$$

Without price caps, fixed premiums incentivize vRESs to strategically bid values higher than zero to avoid decreasing their remuneration. The problem with fixed premiums is that they always result in a tariff deficit if RESs bid values higher than zero. Variable premiums are computed a posteriori considering the yearly levelized production costs, cs_t, market remuneration, and productivity of RESs. In the case of low market prices, they are an added value to the market remuneration of RESs to pay their yearly production costs. Otherwise, RES investors compensate promoters as follows:

$$Diff_s = \sum_{t=1}^{T} (cs_t - rp_t) \times q_t \tag{9}$$

Considering variable premiums, an RES has a guaranteed return independent of its productivity and market prices, which may also result in price "cannibalization". Another solution consists of risk-sharing contracts (RSCs) [12]. RSCs can be indexed to the spot index and are used as a form of risk hedging by sharing the risk of the spot price volatility. When spot prices are higher than the strike price of RSCs, buyers of electrical energy have to financially compensate sellers with a part of the difference between prices, which is computed according to the degree of shared risk, β, as follows:

$$Diff_s = \sum_{t=1}^{T} (sp_t - rp_t)\beta \times q_t \tag{10}$$

If positive, buyers financially compensate sellers. Otherwise, sellers compensate buyers, and their final remuneration is computed as presented in Equation (10). When RSCs are indexed to spot prices, they incentivize RESs to bid values higher than zero to not reduce their remuneration. Indeed, when spot prices are higher than strike prices, RSCs lead to a tariff surplus. RSCs and fixed premiums are the only support schemes that have the potential to avoid price "cannibalization". However, the RSC is the only support scheme with the potential to avoid both price "cannibalization" and the tariff deficit.

4.2. RES Performance Indicators

The levelized cost of energy (LCOE) is the metric that allows the evaluation of the cost of each technology. It considers that investors recover all fixed, cf_n, and variable, cv_n, costs per investment year, n, with a specific technology, during its life cycle, N, according to its production q_n and discount rate, r:

$$LCOE = \frac{\sum_{N=1}^{n} \frac{cf_n + cv_n}{(1+r)^N}}{\sum_{N=1}^{n} \frac{q_n}{(1+r)^N}} \tag{11}$$

The yearly production is computed considering the expected capacity factor of the technology, $\hat{Pf}$, its nominal power Pn, and the number of hours per investment period:

$$q_n = \hat{Pf} \times Pn \times 8760 \tag{12}$$

The production costs of the investor, cs_n, in period n, may consider the weighted average cost of investment (WACC) as follows:

$$cs_n = \frac{(cf_n + cv_n) \times (1 + WACC)^{-1}}{q_n \times (1 + WACC)^{-1}} \tag{13}$$

The WACC consists of the relative cost of every levelized monetary unit of investment. It is considered to define the minimum tax of return for profitable investments in RESs. Historical WACCs may be considered for RES investments [21,22].

5. Case Study on the Negotiation of RSCs for vRES Investments

This study considers a public contest for the investment in 100 MW of wind power plants between the Spanish government and investors in 2010. The Spanish government proposes a support scheme for 12 years, where wind power plants are remunerated based on market results. It proposes RSCs with 50% of risk sharing assumed by investors to avoid small market prices. To make the best business possible, the Spanish government proposes a two-phase public contest for investment in new renewable power plants.

The first phase consists of an auction where the investors propose different strike prices, and the government selects the best offers that comply with the contest requirements. Projects are evaluated according to their expected capacity factors and the proposed strike prices. They receive a bonus if they comply with the required installed capacity. Projects can have power plants in different locations to comply with the requested wind power capacity. If the best project has a score with a difference higher than 2% concerning the second-best project, it is accepted. Otherwise, all projects are invited to the second phase if they have a score difference lower than 2% concerning the best project.

In the second phase, there is a negotiation between the government and the selected investors. Some clauses are negotiated and also the strike price. At this step, all the selected investors know the first proposal of their opponents. Thus, they can make a more competitive proposal in their private negotiations with the government to obtain the deal. This strategy could be advantageous for governments to obtain better deals instead of only having the auction phase.

This study analyzes the impact of the different support schemes in their first (2010) and last years (2022) from the point of view of the promoter (government) and investors (wind farm producer). This study covers extreme market conditions by considering typical years with low (2010) and high (2022) spot prices because of the economic and energy crises, respectively. Furthermore, it also presents a sensibility analysis of the market prices to evaluate and compare the outputs of each support scheme considering different market dynamics. The following section presents the auction phase of the public contest promoted by the government.

5.1. Auction Phase

In the first phase of the public contest, there is an auction where investors propose different strike prices. The public contest consists of investment in new wind farms with a maximum of 100 MW installed power, (Pn_g). Let $\mathcal{A} = \{a_g, a_I\}$ be the set of autonomous agents, being a_g the government agent and $\mathcal{A}_\mathcal{I} = \{a_1, ..., a_i\}$ the set, I, of investor agents, i. Investors' agents can propose investment in wind farms with less than 100 MW, subject to the coupling with other proposals in the same situation. In the case of it being advantageous for the government, it accepts investments with more than 100 MW of installed power.

The merit order for accepting proposals consists first of the best relation between the proposed strike price (sp_i) and the average expected power factor, $\hat{Pf_i}$, of each project and second of the proposed installed power (Pn_i). The installed power differentiates projects in the case of similar points in the first calculation. The bonus is higher depending on how close the installed power is to the required one. The score, $Score_i$, of each project is computed as follows:

$$Score_i = 100 \cdot \left[\left(\frac{k_1 \hat{Pf_i}}{max(\hat{Pf_I})} + \frac{k_2 sp_i}{min(sp_I)} \right) \times \left((1 + k_3 \times (Pn_i / Pn_g) \right) \right] \tag{14}$$

where k_1, k_2, and k_3 are constants that differentiate the weight between the capacity factor (PF), the strike price (SP), and the bonus, respectively. The sum of k_1 and k_2 has to be equal to one, and in this study more importance has been given to SP than to PF. So, values of 0.70 to k_2, 0.30 to k_1, and 0.05 to k_3 (bonus of 5%) can be attributed.

Table 2 presents the main characteristics of the agents with accepted offers.

Table 2. Agents' characteristics.

Agent	Risk Preference	Risk Attitude	Neutral Concession (Cf_n)	Behavior (c)	Initial Price (EUR/MWh)
Government	high aversion	1	10	0.55	89.00
Investor 1	high aversion	1	17	0.70	93.90
Investor 2	aversion	0.5	15	0.15	93.85
Investor 3	small seeking	−0.25	12	0.60	94.70
Investor 4	seeking	−0.5	8	0.30	94.90
Investor 5	small aversion	0.25	17	0.25	95.10
Investor 6	high seeking	−1	10	0.40	95.70

The RSC auction resulted in the following accepted projects for the next phase ordered by merit in Table 3.

Table 3. First phase accepted projects.

Project	Strike Price (EUR/MWh)	Capacity Factor (%)	Installed Power (MW)	Score (%)
3	94.7	26.23	100	101.84
4	94.9	27.11	70	101.65
2	93.85	26.92	30	100.85
5	95.1	26.31	70	100.61
1	93.9	24.54	100	100.58
6	95.7	25.70	100	100.55

Six proposals passed the first phase because the points gap between them is lower than 2%. In the case of only considering this auction-based phase, the public contest winners would be the investors of project 3. However, to increase competition, all investors have access to the first phase results and may negotiate with the government in the second phase.

After this phase, and before the negotiation phase, the government tries to persuade investors that will invest in an installed power lower than the required to invest more (if possible) or ally with other inventors in the same situation. After this approach, investors of projects 2 and 5 strategically ally to improve their score and start the negotiation phase.

5.2. Negotiation Phase

The negotiation phase is where the government will try to decrease the price of all proposals. During the negotiation process, the government agent suggests strike prices between its initial and limit prices, such as for each investor agent. The government evaluates the last proposals of investors and only accepts a proposal after negotiating with all agents, not affecting the negotiation output (multi-party bilateral negotiation). So, at this point, it does not know the results of the merit board of Table 4 but can have an idea during negotiation with all investors. After negotiating with all investors, the government obtained the merit board presented in Table 4.

Analyzing Table 4, it can be concluded that investors 2 and 5 won the public contest. In the following, the negotiation process that led them to win the public contest is presented.

Table 5 presents the initial and limit strike price values of both the government agent and the agent negotiating on behalf of investors 2 and 5.

Table 4. Second phase: projects' score.

Project	Strike Price (EUR/MWh)	Capacity Factor (%)	Installed Power (MW)	Score (%)
2 and 5	92.57	26.5	100	101.16
1	90.49	24.5	100	100.62
3	92.87	26.2	100	100.62
4	93.31	27.1	70	100.26
6	94.65	25.7	100	98.72

Table 5. Agents' initial and limit strike prices

Agent	Initial Price (EUR/MWh)	Limit (EUR/MWh)	Risk Attitude	Neutral Concession (Cf_n)	Behavior (c)
Government	89.00	93.85	1	0.1	0.55
2 and 5	95.80	89.87	0.5	0.15	0.4

Investors 2 and 5 have a risk-averse attitude. So, they will act carefully to achieve a deal. The government has a high risk-averse attitude with the goal of setting a deal. After exchanging seven proposals and counter-proposals, investors 2 and 5 accepted the government proposal of 92.57 EUR/MWh. With this proposal, the alliance of investors 2 and 5 achieved a final score of 101.16%, winning the public contest.

A two-phase CfD with a direct negotiation only with the winner of the first phase of the public contest led to a reduction of only 0.6% in the strike price [15]. Furthermore, a two-phase RSC considering multi-party negotiation of the government with investors that passed the first phase of the public contest led to a reduction in the strike price of 3.2%. So, the results proved the benefit of multi-party negotiation to increase competition and reduce the costs of support schemes. The following section compares different support schemes.

5.3. Comparing Support Schemes

The payment for electricity generated by wind farms in Spain was based on feed-in schemes. In Spain, two types of incentive measures were used, a regulated tariff that consists of an FiT and a market option that consists of an FiP, as presented below:

1. Regulated tariff scheme (FiT): a fixed payment per unit of produced energy with yearly updates considering inflation.
2. Market option (FiP): the payment is computed as the sum of the market price of electricity and a premium. There is a lower limit to guarantee the economic viability of the wind farms and an upper limit (floor and cap, respectively).

The United Kingdom proposed public contests to provide RES incentives. Those public contests consist of CfD auctions where the proposals for investment with lower strike prices won. The CfD contract signed is a regulated one-way CfD. So, the strike price is guaranteed to the investor plus the positive differences between the market price and the strike price, which is the compensation [38]. Furthermore, a CfD auction has been considered with two phases to reduce the strike price, with a strike price of 73.37 EUR/MWh [15].

Currently, the most-used support schemes are fixed and variable premiums. The fixed premium aims at supporting all expected production costs during the support scheme duration. The variable premium considers a yearly compensation of the production costs, which wind power producers cannot receive from markets. Further, these six solutions with the new support scheme based on RSCs are going to be compared.

The analysis considers that the wind farms of projects 2 and 5 started operating in 2010. In 2010, in Spain, the reference value for the FiT was 77.47 EUR/MWh, which is updated based on the Spanish Retail Price Index minus an adjustment factor. The FiP in 2010 had a reference premium of 30.99 EUR/MWh, a lower limit of 75.41 EUR/MWh, and an upper limit of 89.87 EUR/MWh [39]. The CfD auction considers a strike price of 73.90 EUR/MWh. The fixed premium considers the reference premium of 30.99 EUR/MWh without caps. The variable premium has been computed based on the production costs of this wind farm considering an investment of 1602.1 EUR/kWh, an operation and maintenance yearly cost of 23.01 EUR/MWh, a life cycle of 25 years, a support scheme of 12 years, and a WACC of 8.5%.

In 2010, the production costs of the wind power plants of projects 2 and 5 were 64.71 EUR/MWh. These options are going to be economically comparable with the RSC. Furthermore, the prices of support schemes are yearly updated according to the Retail Price Index of the previous year. In 2022, the accumulated inflation of the index in the last year of the support schemes is 16.1%.

Table 6 presents a resume of the incentive options, including their description and price variation between 2010 and 2022. Figures 2 and 3 present the hourly day-ahead prices and wind farm production in 2010 (extrapolated to 2022), respectively.

Table 6. Remuneration options for wind farm investments from 2010 to 2022.

Option	Description
FiT	77.47–89.92 EUR/MWh independent of market price
FiP	30.99–35.97 EUR/MWh reference premium with a limit between 75.41–87.53 and 89.87–104.315 EUR/MWh
CfD	73.90–85.78 EUR/MWh strike price in a regulated one-way CfD contract
Two-phase CfD	73.37–85-29 EUR/MWh SP in a regulated one-way CfD contract
RSC	94.70–109.93 EUR/MWh with 50% risk sharing
Two-phase RSC	92.57–107.45 EUR/MWh with 50% risk sharing
Variable premium	Compensate production costs of 64.71–75.11 EUR/MWh
Fixed premium	30.99–35.97 EUR/MWh
Spot	Hourly day-ahead prices

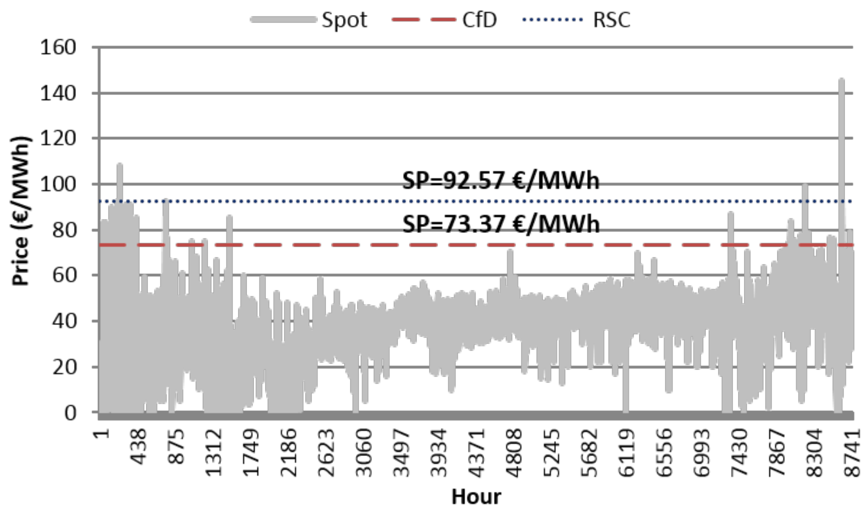

Figure 2. Spanish MIBEL's day-ahead price in 2010.

In Figure 2, the red and blue lines represent the strike prices negotiated in the two-phase auction of the CfD and the RSC, respectively. In 2010, wholesale market prices of electricity were low because the Spanish economy was in crisis. Wind farms had only FiTs and FiPs as support schemes, bidding their near-zero marginal costs in spot markets, which led to price "cannibalization" (see Figure 2). In 2010, these support schemes originated 331 h with prices equal to zero, which is not good for the economic sustainability of producers. Analyzing Figure 2, it can be concluded that only in a few hours during the year was the market price higher than the CfD strike price, which will originate a compensation. Moreover, only for three hours during the year were prices higher than the strike price of the RSC and the government compensated with 50% of the difference. When prices are lower than the RSC strike price, the investor is compensated with 50% of the difference, which occurs for almost the whole year.

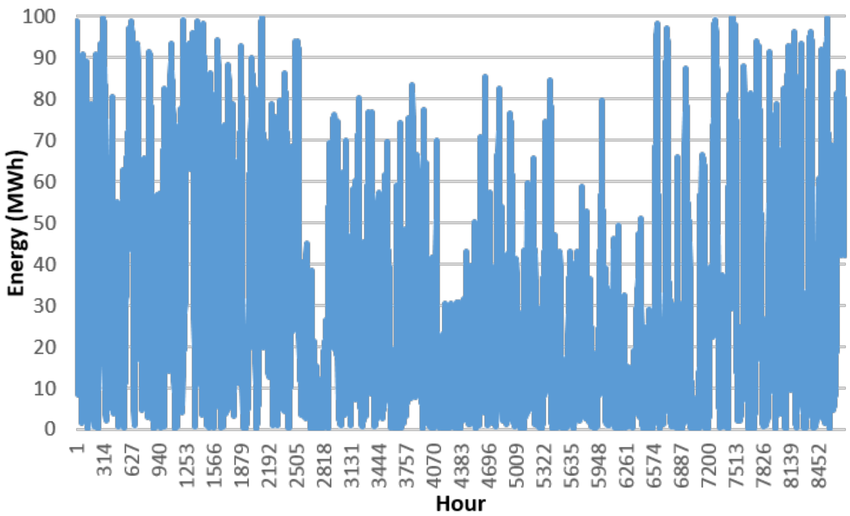

Figure 3. Wind farm production in 2010, extrapolated to 2022.

Figure 3 presents the hourly production of the wind farm, which, during 2010, had a capacity factor of 29.6%. Its productivity was higher than expected (26.5%), which reduced its yearly production costs, with its variable premium being lower than the FiT.

In Table 7 are presented the investor revenues considering the eight different options and the spot-based remuneration of wind farms.

Table 7. Comparing the economic results of each option in 2010.

Market Option	Levelized Price (EUR/MWh)	Remuneration (MEUR)	Return (%)	Government Savings (%)	Deficit (%)
FiT	77.47	20.10	41.7	−19.7	134
FiP	76.88	19.94	40.1	−18.8	132
CfD	73.97	19.19	32.6	−14.3	123
Two-phase CfD	73.55	19.1	31.5	−14	122
RSC	63.90	16.58	6.4	1.2	93.1
Two-phase RSC	62.84	16.30	3.6	2.9	90
Variable premium	64.71	16.79	8.5	0.0	95
Fixed premium	64.09	16.66	6.9	1.0	94
Spot	33.10	8.59	−74.7	48.8	0

Analyzing Table 7, it can be verified that the traditional feed-in options in Spain are too costly compared with the alternatives, mainly in the case of small market prices, especially at crisis times when consumption decreases. Furthermore, while investors consider a minimum WACC of 8.5% to invest, all support schemes give higher returns except for RSCs and the variable and fixed premiums. Thus, all schemes originate a significant tariff deficit (paid by consumers) concerning the market value of the wind energy (spot price) and extra costs concerning the fair remuneration of wind energy (variable premium). Indeed, the variable premium is the support scheme that guarantees investors their target minimum return.

The two-phase RSC is the support scheme with a lower tariff deficit. Even so, wind power producers of projects 2 and 5 have a positive return of 3.6%. Because of small market prices, the RSC final levelized price strongly reduces concerning the strike price from 92.57 EUR/MWh to 62.84 EUR/MWh, which incentivizes wind power producers to bid higher prices. So, it can be concluded that RSCs protect the government at crisis times when consumption decreases and reward investors in growth times when consumption increases. Indeed, while the variable premium is the option with fewer risk to investors, market-based remuneration and RSCs are the options with lower effects on consumers' tariffs. However, these results have been obtained considering the strategic behavior of wind power producers protected by feed-in schemes in 2010. With the end of the first feed-in schemes starting in 2019 and the natural gas crises of 2022, the market prices highly increased in the MIBEL.

Figures 3 and 4 present the hourly extrapolated wind farm production and day-ahead prices in 2022, respectively. Without access to the 2022 production data of the same wind farm, the data were extrapolated from 2010 to 2022, i.e., in 2022, the same hourly wind power production of 2010 was considered.

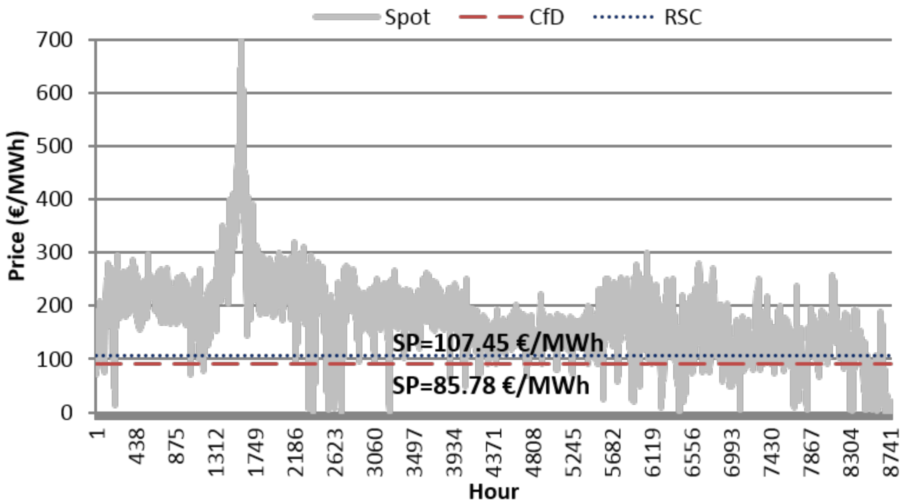

Figure 4. Spanish MIBEL's day-ahead price in 2022.

Analyzing Figure 4, it can be concluded that due to very high spot prices only in 722 and 1437 h the market price was lower than the CfD and RSC strike prices, respectively. While in the case of one-way CfDs the government compensated the wind farm in almost the whole year, in the case of RSCs, it is the government that is compensated.

In Table 8 are presented the investor revenues in 2022 considering the eight different options and the spot-based remuneration of wind farms. Analyzing Table 8, it can be verified that the traditional feed-in options in Spain protect consumers in the case of high spot prices. Furthermore, the variable premium is the support scheme with better results during high-inflation periods because it only remunerates investors based on the negotiated return (WACC). However, by giving a minimum guaranteed return, these support schemes do not provide the dynamic price signals that vRESs need to bid strategically in periods of energy scarcity or excess.

Regulated one-way CfDs and fixed premiums always lead to a tariff deficit, which charges consumers even more in high-inflation periods. RSCs are the best solutions by reducing the tariff deficit during crisis periods and giving an economic surplus in high-inflation periods, reducing consumers' tariffs. Furthermore, during deflation periods, such as in 2010, two-phase public contests are relevant to reduce strike prices to values close to market prices (see Table 7). However, during high-inflation periods, such as in 2022, the benefit of lower strike prices is not so significant (see Table 8).

Against this background, the following section presents a sensibility analysis to verify the variations in the remuneration of the wind farm considering an increase and decrease in the 2010 market prices.

Table 8. Comparing the economic results of each option in 2022.

Market Option	Levelized Price (EUR/MWh)	Remuneration (*M*EUR)	Return (%)	Government Savings (%)	Deficit (%)
FiT	89.92	23.33	39.36	−19.7	−48.5
FiP	103.38	26.82	67.39	−37.6	−40.8
CfD	178.44	46.29	123.70	−137.6	2.2
Two-phase CfD	178.40	46.28	123.61	−137.5	2.2
RSC	142.77	36.91	148.38	−89.4	−18.5
Two-phase RSC	141.03	36.59	145.80	−87.8	−19.2
Variable premium	75.11	19.49	8.50	0.0	−57.0
Fixed premium	210.59	54.63	190.66	−180.4	20.6
Spot	174.62	45.30	115.74	−132.5	0.0

5.4. Sensibility Analysis

As FiTs are independent of the market prices, they serve as a reference for the obtained revenues concerning the other options.

Figure 5 presents the results of a sensibility analysis where each support scheme revenue varies concerning the FiT, considering a decrease or increase in the reference market price of 2010. The results presented in Figure 5 consider as a reference the average market prices, wind investment costs, and FiTs of 2010. In 2010, the wind energy value and the production costs of the studied wind farm were 33.10 EUR/MWh and 64.71 EUR/MWh, respectively.

Against this background, Figure 5 can be used to evaluate the market outcomes of the different support schemes, considering different market dynamics. It can be used directly to evaluate the wind farm remuneration from each support scheme considering dynamic market prices that vary from 0 (−100%) to 132.4 EUR/MWh (200%), which already covers almost all yearly prices of European day-ahead markets [5,40,41]. However, considering the slopes of the line of each support scheme, each line can be extrapolated to lower or higher prices. Adapting those lines for lower prices can be used to evaluate the market outcomes of each support scheme in the case of negative prices. Furthermore, annual average spot prices can be evaluated as presented, but also different price granularity, e.g., hourly spot prices.

The sensibility analysis considers the investment and production costs (64.71 EUR/MWh) of the studied wind farm in 2010. Considering wind farms with higher or lower production costs, the support schemes' market outcomes (lines) must be subject to down or up vertical translation, respectively, i.e., shifting the base lines down or up in the direction of the y-axis. Considering that the investment costs of onshore wind fall as the technology is more mature, while the support schemes can be adapted and have similar behaviors for recent investments, the relative market-based remuneration (dashed gray line) of onshore wind has highly increased nowadays.

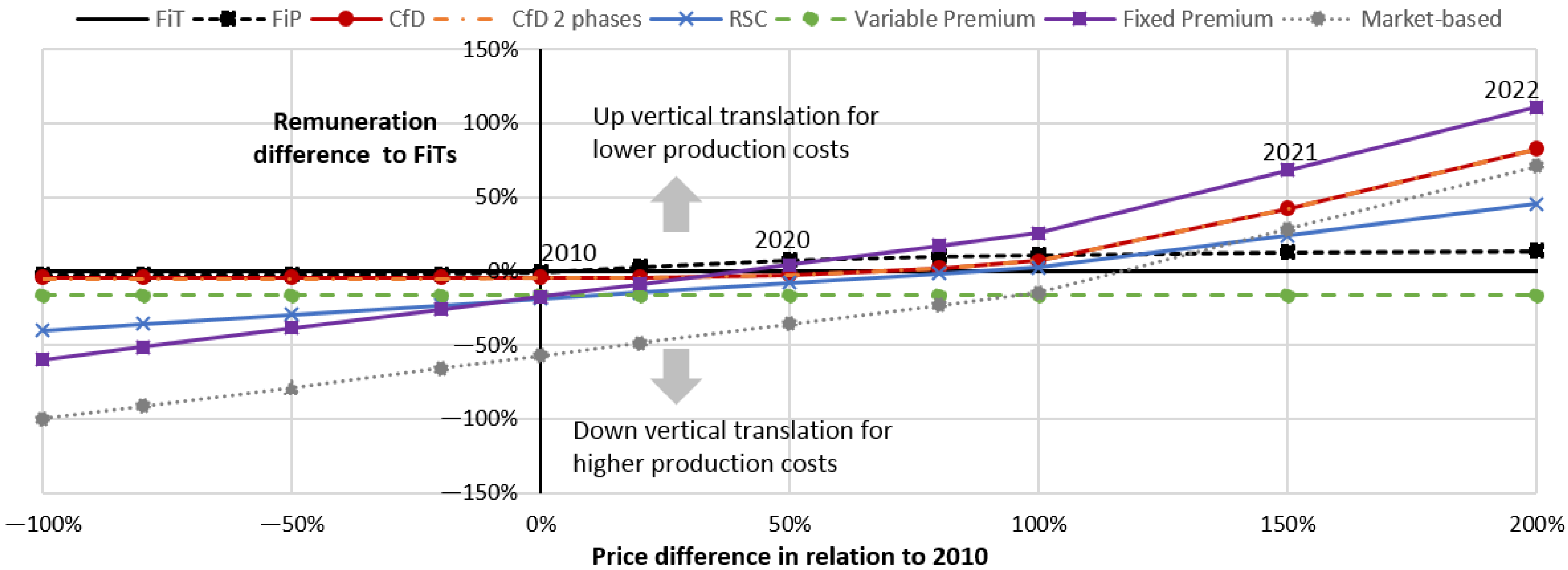

Figure 5. Sensibility analysis of each option's revenue variation to market prices concerning FiTs. Market prices (33.10 EUR/MWh), FiTs, onshore wind investment costs, generation, and production costs (64.71 EUR/MWh) from 2010 are the reference of the analysis. Revenues of support schemes (lines) can go up and down, considering lower or higher production costs concerning the 2010 reference value, respectively. Furthermore, the presented price difference can be extended by considering the different slopes of support schemes' lines.

The variable premium is the support scheme that provides to the investors of projects 2 and 5 the minimum acceptable return of 8.5% considering the investment costs of wind power plants in 2010 (dashed green line). It is independent of market prices, as FiTs, giving a remuneration 16% lower when compared with the employed FiTs in Spain. So, remunerations higher than −16% concerning FiTs provide the economic sustainability that investors require. However, when the market-based remuneration of those power plants is lower than the support schemes' remuneration, it originates a tariff deficit paid by end-use consumers.

The MIBEL started operating in 2008. In Spain, the electricity market prices were stable from 2008 to 2019 but started increasing in 2020 after (i) the pandemic lockdown since 2020; (ii) an alteration in the legislation that changed the market price caps from 0 and 180.3 to −500 and 3000 EUR/MWh in 2021; and (iii) the natural gas crisis in Europe since 2022. Indeed, in 2022, wholesale electricity prices achieved historical maximums, with an average value four times higher than in 2010, being controlled by the Iberian maximum price cap for natural gas technologies [42].

Analyzing Figure 5, it can be concluded that, after 2021, the wind power plants of projects 2 and 5 do not need support schemes to be economically sustainable, mainly because of the high market prices triggered by the new legislation and the natural gas crisis. However, the natural gas crisis in Europe has been partially mitigated in the MIBEL by the price cap of natural gas.

Concerning the traditional support schemes used in 2010, it is concluded that regulated one-way CfD auctions are better options for the government than FiPs, because only for a very high increase in market prices (around 100%) is the revenue of wind farms higher. The CfD auction only differs when market prices decrease, and then the two-phase CfD action gives lower returns to wind farms. Furthermore, it is understandable why the majority of wind farm investors in Spain choose FiPs instead of FiTs. In the worst case, FiPs give less than 2.5% of revenue, and, just for a decrease in the market prices of around 15%, it is the worst. In the best scenario, this option can give them more than 15% of income concerning FiTs if the market prices increase by more than 40% concerning the reference. FiPs could be a good solution if well designed, but what happened is that the reference premium and the lower limit were too high, especially when comparing both limits with the FiT price. The lower limit should decrease to a relevant value that gives the same benefit to the government at crisis times and in high-inflation or economic growth times (less than 15% of revenues instead of 2.5% compared with the regulated tariff, as can be verified in the sensibility analysis). This solution protects consumers and decreases the tariff deficit at crisis times.

Concerning the price risk of support schemes, it can be verified that regulated one-way CfDs and fixed premiums always originate a tariff deficit, i.e., originate an RES remuneration always higher than the market-based remuneration. They are similar to FiPs by slightly hedging the risk of small prices when FiPs significantly hedge the risk of high prices. Concerning FiTs, FiPs, and variable premium support schemes, regulated one-way CfDs may slightly reduce the tariff deficit for small prices but do not protect consumers in the case of high prices. RSCs significantly hedge the price risk in the case of high prices, originating a tariff surplus, and slightly hedge the price risk in the case of small prices, originating a tariff deficit lower than all other support schemes except fixed premiums.

Concluding, while FiTs, RSCs, and variable premiums are the only presented support schemes that can provide a tariff surplus, RSCs and fixed premiums are the only ones that incentivize wind farms to bid prices higher than zero. Furthermore, bidding prices higher than zero are very important to avoid price "cannibalization" and reduce the need for externalities, such as support schemes to non-mature RESs, capacity mechanisms to fossil fuel power plants, and other incentives. Against this background, the RSC is the best support scheme by hedging against the volatility of market prices, incentivizing RES bids with higher prices, and avoiding the tariff deficit.

6. Conclusions

This paper has presented the key features of a negotiation model for the bilateral contracting of renewable energy source (RES) support schemes in multi-agent electricity markets, emphasizing concession strategies, risk management, and risk-sharing contracts (RSCs).

The main problem of RES support schemes is that they reduce market prices because of the close-to-zero bids of RESs, which originate a price "cannibalization". Furthermore, the price "cannibalization" originates the (i) need for capacity mechanisms to economically support traditional generation and (ii) tariff deficits, i.e., the negative difference between the market values of RESs and their remuneration. Normally, retail tariffs are significantly higher than the wholesale price of electrical energy and increase because of the tariff deficit and the costs of capacity mechanisms. However, the energy crisis of 2022 led to a new paradigm, where risk-hedged retailers proposed retail prices lower than wholesale spot prices. In contrast, risk-seeking retailers had to increase their tariffs more than once a year to avoid bankruptcy. Risk-hedging solutions, such as RSCs, can increase the benefit of all parties in both high-inflation and deflation periods.

The support schemes used in Spain are feed-in tariffs and premiums. The United Kingdom also considered regulated one-way contracts for difference (CfD) auctions. An alternative version of these auctions has been presented, considering a negotiation phase to reduce the strike price of CfDs. Currently, fixed and variable premiums are the most-used support schemes in new RES investments.

This article has presented a study focusing on a public contest for trading RSCs between the Spanish government and wind farms' investors . The public contest has two phases. The first phase consists of an auction where investors can present their projects and propose strike prices. The best-ranked projects can participate in the second phase, being aware of the first phase results. This phase consists of a multi-party private negotiation with the government. After this phase, the project with the highest score wins the public contest and signs an RSC with the government. This study compared this RSC with the three traditional support schemes used in Spain and the UK, the alternative two-phase regulated one-way CfDs, the spot price, and fixed and variable premiums. Fixed premiums and regulated one-way CfDs led to tariff deficits by providing a premium over wholesale market prices. Variable premiums and FiTs led to price "cannibalization" by guaranteeing a fixed return to investors, which does not incentivize variable RESs (vRESs) bidding prices higher than their near-zero marginal costs. Results from the study prove the benefit of using RSCs to avoid both price "cannibalization" and the tariff deficit by incentivizing bids higher than zero and hedging against the market price volatility. Furthermore, the study also proves that open proposals increase competition and reduce the strike prices of support schemes. The second phase of the public contest reduced the price by 3.2%.

Future work aims at testing the strategic bidding of RESs considering different support schemes to verify the behavior of these players and the outcome of these schemes under different market dynamics. Furthermore, it also aims at performing several experiments to empirically evaluate the outputs of key components of the agents, notably the concession-making strategies and their associated tactics while negotiating support schemes.

Funding: This work has received funding from the EU Horizon 2020 research and innovation program under project TradeRES (grant agreement No 864276).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The market results of the Iberian market of electricity are available at https://www.mercado.ren.pt/EN/Electr/MarketInfo/MarketResults/Pages/default.aspx (accessed on 16 February 2023).

Conflicts of Interest: The author declares no conflict of interest.

Abbreviations

CfD	contract for differences
FiT	feed-in tariff
FiP	feed-in premium
LCOE	levelized cost of energy
MIBEL	Iberian market of electricity
PF	capacity factor
PPA	power purchase agreement
RES	renewable energy source
RSC	risk-sharing contract
SP	strike price
vRES	variable renewable energy source
WACC	weighted average cost of investment
Parameters	
β	shared risk
λ	risk attitude
c	agent's behavior
C_{fn}	concession factor of risk-neutral
fp_t	fixed premium
k_1	weight of score function term 1 (strike price)
k_2	weight of score function term 2 (capacity factor)
k_3	weight of score function term 3 (bonus)
max	maximum value of item
$maxp_t$	maximum price cap
min	minimum value of item
$minp_t$	minimum price cap
Pn	nominal power
Pf	capacity factor
Indices	
$\mathcal{A}$	set of agents
i	agent index
I	number of investor agents
t	period
$\mathcal{T}$	number of periods
n	investment period
N	number of investment periods
Variables	
Π_s	seller's remuneration
a	agent
C_f	concession factor
cf_t	fixed production costs
cs_t	production costs
cv_t	variable production costs
$Diff_s$	seller's pay-off
p	price
q	quantity
r	interest rate
Rp	reference price vector
rp	reference price
$Score$	project's score
Sp	strike price vector
sp	strike price

References

1. Hunt, S.; Shuttleworth, G. *Competition and Choice in Electricity*; Wiley: Chichester, UK, 1996.
2. Shahidehpour, M.; Yamin, H.; Li, Z. *Market Operations in Electric Power Systems*; Wiley: Chichester, UK, 2002.
3. Algarvio, H.; Lopes, F.; Couto, A.; Estanqueiro, A. Participation of wind power producers in day-ahead and balancing markets: An overview and a simulation-based study. *WIREs Energy Environ.* **2019**, *8*, e343. [CrossRef]
4. Strbac, G.; Papadaskalopoulos, D.; Chrysanthopoulos, N.; Estanqueiro, A.; Algarvio, H.; Lopes, F.; de Vries, L.; Morales-España, G.; Sijm, J.; Hernandez-Serna, R.; et al. Decarbonization of Electricity Systems in Europe: Market Design Challenges. *IEEE Power Energy Mag.* **2021**, *19*, 53–63. [CrossRef]
5. Algarvio, H.; Lopes, F.; Couto, A.; Santana, J.; Estanqueiro, A. Effects of Regulating the European Internal Market on the integration of Variable Renewable Energy. *WIREs Energy Environ.* **2019**, *8*, e346. [CrossRef]
6. Kirschen, D.; Strbac, G. *Fundamentals of Power System Economics*; Wiley: Chichester, UK, 2018.
7. Algarvio, H. Multi-step optimization of the purchasing options of power retailers to feed their portfolios of consumers. *Int. J. Electr. Power Energy Syst.* **2022**, *142*, 108260. [CrossRef]
8. Makijenko, J.; Burlakovs, J.; Brizga, J.; Klavins, M. Energy efficiency and behavioral patterns in Latvia. *Manag. Environ. Qual. Int. J.* **2016**, *27*, 695–707. [CrossRef]
9. Aven, T.; Renn, O. *Risk Management and Governance: Concepts, Guidelines and Applications*; Springer: Heidelberg, Germany, 2010.
10. Hopkin, P. *Fundamentals of Risk Management: Understanding, Evaluating and Implementing Effective Risk Management*, 2nd ed.; Kogan Page Publishers: London, UK, 2012.
11. Algarvio, H.; Lopes, F.; Couto, A.; Estanqueiro, A.; Santana, J. Variable Renewable Energy and Market Design: New Market Products and a Real-world Study. *Energies* **2019**, *12*, 4576. [CrossRef]
12. Algarvio, H. Risk-Sharing Contracts and risk management of bilateral contracting in electricity markets. *Int. J. Electr. Power Energy Syst.* **2023**, *144*, 108579. [CrossRef]
13. Brigatto, A.; Fanzeres, B. A soft robust methodology to devise hedging strategies in renewable energy trading based on electricity options. *Electr. Power Syst. Res.* **2022**, *207*, 107852. [CrossRef]
14. Algarvio, H.; Lopes, F. Agent-based Retail Competition and Portfolio Optimization in Liberalized Electricity Markets: A Study Involving Real-World Consumers. *Int. J. Electr. Power Energy Syst.* **2022**, *137*, 107687. [CrossRef]
15. Algarvio, H.; Lopes, F.; Santana, J. Renewable Energy Support Policy Based on Contracts for Difference and Bilateral Negotiation. In *Highlights in Practical Applications of Agents, Multi-Agent Systems, and Trust-Worthiness. The PAAMS Collection*; Springer: Cham, Switzerland, 2020; pp. 293–301.
16. European Union: Directive 2009/28/EC of the European Parliament and of the Council on the Promotion of the Use of Energy from Renewable Sources and Amending and Subsequently Repealing Directives 2001/77/EC and 2003/30/EC, 23 April 2009. Available online: http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32009L0028 (accessed on 16 February 2023).
17. European Union: The Promotion of the Use of Energy from Renewable Sources, Directive (EU) 2018/2001, 11 December 2018. Available online: http://data.europa.eu/eli/dir/2018/2001/oj (accessed on 16 February 2023).
18. Yu, J.; Ju, F.; Wahab, M.; Agyekum, E.B.; Matasane, C.; Uhunamure, S.E. Estimating the Effects of Economic Complexity and Technological Innovations on CO2 Emissions: Policy Instruments for N-11 Countries. *Sustainability* **2022**, *14*, 16856. [CrossRef]
19. Yang, C.; Namahoro, J.P.; Wu, Q.; Su, H. Renewable and Non-Renewable Energy Consumption on Economic Growth: Evidence from Asymmetric Analysis across Countries Connected to Eastern Africa Power Pool. *Sustainability* **2022**, *14*, 16735. [CrossRef]
20. Rathod, A.A.; Subramanian, B. Scrutiny of Hybrid Renewable Energy System for Control, Power Management, Optimization and Sizing: Challenges and Future Possibilities. *Sustainability* **2022**, *14*, 16814. [CrossRef]
21. Franc-Dabrowska, J.; Madra-Sawicka, M.; Milewska, A. Energy Sector Risk and Cost of Capital Assessment—Companies and Investors Perspective. *Energies* **2021**, *14*, 1613. [CrossRef]
22. Dobrowolski, Z.; Drozdowski, G.; Panait, M.; Apostu, S.A. The Weighted Average Cost of Capital and Its Universality in Crisis Times: Evidence from the Energy Sector. *Energies* **2022**, *15*, 6655. [CrossRef]
23. Hausman, E.; Hornby, R.; Smith, A. Bilateral Contracting in Deregulated Electricity Markets. Report to the American Public Power Association, Synapse Energy Economics. April 2008. Available online: https://citeseerx.ist.psu.edu/document?repid=rep1&type=pdf&doi=ade9d3a2f4632eec104f08f109d9ba6bf01305fb (accessed on 16 February 2023).
24. Ramírez, F.J.; Honrubia-Escribano, A.; Gómez-Lázaro, E.; Pham, A.T. Combining feed-in tariffs and net-metering schemes to balance development in adoption of photovoltaic energy: Comparative economic assessment and policy implications for European countries. *Energy Policy* **2017**, *102*, 440–452. [CrossRef]
25. Bohland, M.; Schwenen, S. Renewable support and strategic pricing in electricity markets. *Int. J. Ind. Organ.* **2022**, *80*, 102792. [CrossRef]
26. Anatolitis, V.; Azanbayev, A.; Fleck, A.K. How to design efficient renewable energy auctions? Empirical insights from Europe. *Energy Policy* **2022**, 166, 112982. [CrossRef]
27. Lopes, F.; Algarvio, H.; Santana, J. Agent-based simulation of electricity markets: Risk management and contracts for difference. In *Agent-Based Modeling of Sustainable Behaviors*; Springer: Cham, Switzerland, 2017; pp. 207–225.
28. Algarvio, H. The Role of Local Citizen Energy Communities in the Road to Carbon-Neutral Power Systems: Outcomes from a Case Study in Portugal. *Smart Cities* **2021**, *4*, 840–863. [CrossRef]

29. European Commission. Regulation (EU) 2019/943 of the European Parliament and of the Council on the Internal Market for Electricity. 5 June 2019. Available online: http://data.europa.eu/eli/reg/2019/943/oj (accessed on 16 February 2023).
30. Prol, J.; Steininger, K.; Zilberman, D. The cannibalization effect of wind and solar in the California wholesale electricity market. *Energy Econ.* **2020**, *85*, 104552. [CrossRef]
31. Hinderks, W.J.; Wagner, A. Factor models in the German electricity market: Stylized facts, seasonality, and calibration. *Energy Econ.* **2020**, *85*, 104351. [CrossRef]
32. Algarvio, H. Agent-based model of citizen energy communities used to negotiate bilateral contracts in electricity markets. *Smart Cities* **2022**, *5*, 1039–1053. [CrossRef]
33. Baarslag, T.; Hendrikx, M.J.; Hindriks, K.V.; Jonker, C.M. Learning about the opponent in automated bilateral negotiation: A comprehensive survey of opponent modeling techniques. *Auton. Agents Multi-Agent Syst.* **2016**, *30*, 849–898. [CrossRef]
34. Marsa-Maestre, I.; Lopez-Carmona, M.A.; Ito, T.; Zhang, M.; Bai, Q.; Fujita, K. *Novel Insights in Agent-Based Complex Automated Negotiation*; Springer: Berlin/Heidelberg, Germany, 2014; p. 535.
35. Algarvio, H. Management of Local Citizen Energy Communities and Bilateral Contracting in Multi-Agent Electricity Markets *Smart Cities* **2021**, *4*, 1437–1453. [CrossRef]
36. Raiffa, H. *The Art and Science of Negotiation*; Harvard University Press: Cambridge, UK, 1982.
37. Pratt, J. Risk Aversion in the Small and in the Large. *Econometrica* **1964**, *32*, 122–136. [CrossRef]
38. Grubb, M.; Newbery, D. UK Electricity Market Reform and the Energy Transition: Emerging Lessons. *Energy J.* **2018**, *39*. [CrossRef]
39. Ministry of Industry, Energy and Tourism. The National Action Plan for Renewable Energy (2011–2020). Ministry of Industry, Energy and Tourism, Government of Spain, Madrid. 2010. Available online: http://pvtrin.eu/assets/media/PDF/EU_POLICIES/National%20Renewable%20Energy%20Action%20Plan/202.pdf (accessed on 16 February 2023).
40. ACER. ACER Market Monitoring Report—2015. 2015. Available online: https://acer.europa.eu/Official_documents/Acts_of_the_Agency/Publication/ACER_Market_Monitoring_Report_2015.pdf (accessed on 16 February 2023).
41. ACER. ACER Market Monitoring Report 2020: Electricity Wholesale Market Volume. 2021. Available online: https://acer.europa.eu/Official_documents/Acts_of_the_Agency/Publication/ACER%20Market%20Monitoring%20Report%202020%20%E2%80%93%20Electricity%20Wholesale%20Market%20Volume.pdf (accessed on 16 February 2023).
42. Grubb, M.; Drummond, P.; Maximov, S. Separating electricity from gas prices through Green Power Pools: Design options and evolution. *Inst. New Econ. Think. Work. Pap. Ser.* **2022**, *193*.