Assessing potential distortions under production-based CfDs on the German electricity market

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***Abstract*— EU legislation mandates the introduction of two-way Contracts for Difference (CfDs) for renewable energy (RE) investment support starting in 2027. Different schemes have been proposed, ranging from more conventional production-based CfDs that may distort market signals and incentivize undesirable producer behavior to more complex production-independent CfDs that aim to avoid distortions. This paper empirically analyzes the implications of production-based CfDs on the German day-ahead and intraday markets from 2020 to 2024. We quantify the frequency and magnitude of inefficient dispatch incentives linked to different CfD designs. The results indicate that most distortions occur in clawback years and on the day-ahead market, suggesting potential corrections through dynamic clawback design. While distortions in intraday markets are less prevalent, they are more difficult to fix by adjustments in the design of production-based CfDs. Our research highlights the need for further investigation to inform decisions regarding the adoption of particular CfD designs.**

***Index Terms*--Contract for Difference, Market distortions, Renewable energy, Support schemes**

I. Introduction

Recent EU electricity market design legislation [1] mandates that under certain conditions, investment support for the deployment of renewable energy (RE) plants should take the form of two-way Contracts for Difference (CfDs) from 2027 onwards. Motivated by high electricity prices and profits during the energy crisis, two-way CfDs introduce a payback obligation for producers if the reference market price is above the agreed strike price (see [2] for a detailed overview of various proposed and implemented CfD designs). Recently, the German federal ministry for Economic Affairs and Climate Action conducted a stakeholder process on electricity market design, which concluded in an option paper on an 'Electricity Market Design of the Future' [3] that is compatible with Germany's ambitious RE targets [4]. High shares of RE present various challenges, including setting efficient incentives for dispatch, siting and plant design decisions [5].

Most (one-way) CfD schemes for renewable electricity currently in place in EU member states are production-based, which means that support payments and payback obligations are calculated based on the actual feed-in of individual RE plants. Under certain circumstances, production-based CfDs may distort market price signals and set undesirable incentives for producers' dispatch and bidding behavior on short-term electricity markets. Producers may be incentivized to curb production at positive spot market prices to avoid payback obligations or to continue feed-in at negative spot market prices to avoid foregoing support payments. This is problematic, because high spot prices indicate a shortage of electricity supply, negative prices indicate oversupply – both can be exacerbated by such market distortions. In addition, price-formation on short-term electricity markets may be distorted if producers internalize their opportunity costs arising from support payments and payment obligations into their bids.

As an alternative that avoids these distortions, production-independent CfDs have been proposed (e.g. [6–8]), for which support payments and payback obligations are not based on an individual plant's feed-in, but on its potential electricity production. By decoupling payments from individual plants' feed-in, electricity price signals are passed on to producers in an undistorted manner. In addition, by making support payments independent of feed-in, producers are hedged against volume risks arising from plant unavailability or negative prices. On the other hand, production-independent CfDs likely come at the expense of increased complexity and substantial implementation challenges. For instance, defining a suitable reference against which the payments under production-independent CfDs are determined has proven difficult so far and potentially introduces a new base risk for generators of deviating from the reference. In summary, different CfD schemes provide different risk allocations between RE producers and the government and set varying incentives for dispatch, siting and plant design [9]. Notably, the German option paper indicates a clear preference for production-independent CfD schemes.

To evaluate the significance of the respective advantages and drawbacks of production-based and production-independent CfDs, it is important to quantify the size of these effects. However, the discussion around different CfD schemes has been led almost exclusively based on qualitative arguments, providing very little quantitative evidence. A notable exception has been a quantitative analysis of conflict situations on the Dutch day-ahead and balancing markets under two different

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production-based CfD designs by ENTSO-E [10]. In this paper, we elaborate on this approach and address the lack of quantitative analyses by empirically analyzing the significance of potential distortions on the German day-ahead and intraday markets for 2020-2024 under a production-based CfD design.

The remainder of the paper is structured as follows: In Section II, we describe the data and methodology used for the analysis. Section III presents our results on the frequency and magnitude of distortions. We discuss caveats and policy implications in Section IV before concluding in Section V.

II. Data and Methodology

To determine the frequency and magnitude of problematic incentives for RE generators under production-based CfDs, we analyze price data for the German day-ahead and intraday markets for 2020-2024. Besides being the most recent and thus reflecting current market dynamics, the past five years contain extreme low-price years (2020), high-price years (2022) and years closer to multi-annual averages (2021, 2023, 2024). Table I gives an overview of the different prices and other input data used for the analysis.

TABLE I. Overview of Input Data

Year	Ø DA price	Market value PV	Strike price PV	Support Payment	Ø ID1 price
2020	30.47	24.58	51.34	26.76	32.39
2021	96.85	75.52	54.93	– 20.59	100.09
2022	235.45	223.06	53.88	– 169.18	239.23
2023	95.18	72.00	52.79	– 19.21	95.80
2024	79.46	46.24	53.26	7.02	78.38

All prices are in €/MWh.

The average day-ahead price refers the technology-uniform volume-weighted mean of the hourly day-ahead price, while the market value of PV is the annual mean of the hourly day-ahead price weighted by the electricity production by PV plants. Both are available on the transparency platform of the German TSOs [11]. The strike prices reported here refer to the average strike price of successful bids in auctions for utility-scale solar PV that entered into operation in the year of observation and are taken from the German federal network agency [12]. We focus on utility-scale PV, because this type of RE plants is easy to curtail and typically operated by large, professional actors.

We consider a production-based CfD design with an annual reference period and a single strike price (i.e. no cap and floor design). No support is paid out during periods with negative day-ahead prices. The support payment is calculated as the difference between the strike price *SP* and the annual market value MV_y and can be negative, which means that RE generators have a payback obligation to the state. The annual clawback CB_y can be regarded as a negative support payment obligation or a positive payment from the generator to the state, as formulated in Eq. (1).

$$CB_y = -(SP - MV_y) \qquad (1)$$

In addition, we use data on continuous trades on the intraday market by EPEX Spot [13]. We consider three different indices of the volume-weighted average price of bilateral trades referring either to quarter-hourly (e.g. delivery of 10 MWh for 50 €/MWh from 08:30 to 08:45) or hourly products (e.g. delivery from 08:00 to 09:00):

- The IDFULL index consists of the weighted average of all trades conducted over the entire time a product is traded;
- The ID3 index only takes into account the last 3 hours during which the product is traded, typically reflecting the most liquid trading interval;
- The ID1 index only considers the last hour before delivery, representing short-term imbalance needs of the market and often having the largest volatility of the three indices. We thus focus on this index to obtain an estimate of the upper bound of problematic incentives.

For the further analysis, we assume that RE generators behave rationally and aim to maximize their profits. We further assume that marginal costs for producing electricity or curtailing RE plants are negligible. Problematic incentives occur when generators' profit maximization leads to a different behavior than what would be optimal from a system perspective, i.e. producing electricity if spot market prices are greater than marginal cost.

First, we analyze the relevance of distortions in support years. We examine whether there was an incentive for producers to keep producing at negative intraday prices rather than curtail their plants, which would be efficient from a system perspective, to avoid foregoing the support payment. Mathematically, this is the case when the additive inverse of the support payment is less than the negative intraday price (cf. Eq. (2)). This is only relevant for hours with positive day-ahead prices, since no support is paid in hours with negative prices.

$$-(SP - MV_y) < ID_t < 0 < DA_t \qquad (2)$$

Next, we analyze distortions arising from clawback obligations in high-price years where the market value is greater than the strike price. In hours with relatively low, but positive spot market prices, there is an incentive for RE generators to curtail their plants to avoid having to pay the clawback. More precisely, this is the case when the day-ahead market price falls below the clawback (which is determined ex-post on an annual basis) as shown in Eq. (3). If generators foresee the clawback exceeding the day-ahead price, they will either not bid in the day-ahead auction or only submit a bid that is greater than the clawback, both of which leads to a steeper supply curve and higher day-ahead market prices.

$$0 < DA_t < CB_y \qquad (3)$$

This problematic incentive can be corrected by a dynamic clawback design, i.e. by adjusting the size of the clawback to the day-ahead market price as shown in Eq. (4) to set efficient dispatch and bidding incentives on the day-ahead market.

$$CB_t^{dyn} = max\,[min\,(CB_y\,;\,DA_t);\,0] \qquad (4)$$

If generators have submitted a bid on the day-ahead market and are awarded in the merit order (either with a fixed or a dynamic clawback), they may have an incentive to fulfil their delivery obligations by buying electricity on the intraday market and curtailing their plants instead of generating the electricity (and having to pay the clawback). This is the case whenever the positive intraday price falls below the clawback.

$$0 < ID_t < CB_y < DA_t \qquad (5)$$

Eq. (5) shows the criterion for problematic incentives for the case with a fixed clawback, while Eq. (6) gives the modified criterion for the case of a dynamic clawback.

$$0 < ID_t < CB_t^{dyn} \quad and \quad DA_t > 0 \tag{6}$$

We identify the number of (quarter) hours where the above conditions (2), (3), (5) and (6) are satisfied, indicating problematic incentives. In addition, we analyze the traded volumes and price spreads these distortions correspond to.

III. RESULTS

In this section, we report the absolute and relative frequency as well as the magnitude of the different distortions in turn.

A. *Distortions in support years on the intraday market*

First, we turn to distortions in support years, which are also relevant under ons-sided CfDs, such as Germany's current sliding premium scheme. Figure 1 plots the Day-Ahead price against the ID1 index for all quarter hours of the year, highlighting the ones with problematic incentives in orange. In total, condition (2) was satisfied in 2.9 % of quarter hours in 2020, presenting incentives for inefficiently high RE feed-in. This is substantially more than in 2024, the other support year for utility-scale PV in the observation period, where only 1.8 % of quarter hours had problematic incentives (see Table II). This can be explained by the higher support payment in 2020, which makes a larger range of intraday prices problematic.

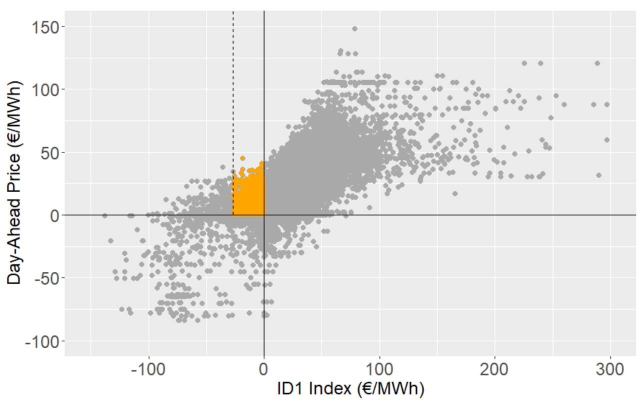

Figure 1. Problematic incentives on the intraday market in 2020.

The average traded ID1 volume in problematic hours was relatively similar in both years with 244 and 231 MWh respectively. To assess the relevance of these volumes for the electricity market, we compare them to the actual feed-in of solar PV in the relevant quarter hours. The share of the average traded ID1 volume to the average total electricity production in problematic quarter hours was 1.78 % in 2020 and 1.70 % in 2024. Together with the fact that traded ID1 volumes did not significantly differ between problematic and unproblematic quarter hours, our results suggest that only a relatively small share of generators make use of the existing incentives.

We also examine the effect of different strike prices on the frequency of distortions. In general, higher strike prices lead to higher support payments for a given market value, which in turn leads to distortions for a larger interval of negative intraday prices according to Eq. (2). To quantify this effect, we repeat the analysis with different higher strike prices. We find that higher strike prices up to 200 €/MWh lead to a progressively larger number of distortions, but only to a limited extent (see Table IV in the appendix). This is because intraday prices are typically only moderately negative and very rarely fall below 100 €/MWh. It should be noted that this effect is largest for ID1 prices, since they show the highest volatility and thus typically become negative the most.

TABLE II. DISTORTIONS IN SUPPORT YEARS ON THE INTRADAY MARKET

Year	Payment (€/MWh)	Problematic quarter hours	Ø Spread (€/MWh)	Avg. traded ID volume (MWh)
2020	26.76	1002 (2.9 %)	17.78	243.67
2024	7.02	638 (1.8 %)	3.76	230.91

B. *Distortions in clawback years on the day-ahead market*

Turning to distortions in clawback years, we first examine hours in which the day-ahead price falls below the clawback, leading to problematic incentives for inefficiently high RE curtailment and inflated bidding on the day-ahead market as described in Eq. (3). As shown in Figure 2, day-ahead prices were lower than the annual clawback in up to one third of the hours in 2022. The number of hours with problematic incentives on the day-ahead market was much lower in 2021 and 2023, with 3.0 % and 5.6 % respectively (see Table III). Intuitively, the size of the clawback is a major determinant of the frequency of distortions as a larger clawback makes more hours problematic for a given distribution of prices. However, the distribution of prices itself is also an important factor. While 2021 and 2023 had very similar average prices and clawback payments, prices were a lot more volatile in 2021 due to onset of the gas crisis, which explains why the frequency of distortive incentives was almost twice as high. This is indicated by a larger coefficient of variation of day-ahead prices (0.76 in 2021 vs. 0.5 in 2023).

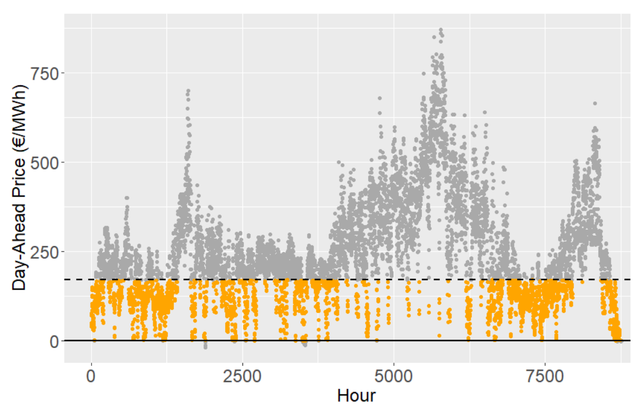

Figure 2. Problematic incentives on the day-ahead market in 2022.

In general, longer reference periods are less likely to lead to a clawback due to the longer period over which (technology-specific) prices are averaged [2]. When repeating the analysis with a monthly reference period, we find that this holds true for the years 2021 and 2023. Due to the fluctuation of day-ahead prices over the year, the market value of PV is greater than the strike price in some months, while it is less than the strike price in others. However, the size of the clawback is naturally larger in some months compared to annual average. As a result, we find more hours with problematic incentives in those years when using a monthly reference period instead of an annual one (compare Table VII in the appendix). For 2022, monthly market values were greater than the strike price in all months due to very high price level during the gas crisis. Interestingly, we observe a much lower number of problematic hours in 2022 when using a monthly reference period (20.0 %) compared to an annual one. This can be explained by the fact that for months with relatively low market values, there are much fewer hours where the day-ahead price falls below the monthly clawback compared to the annual clawback.

TABLE III. DISTORTIONS IN CLAWBACK YEARS ON THE DAY-AHEAD MARKET

Year	Payment (€/MWh)	Problematic hours	Ø Spread (€/MWh)
2021	– 20.59	265 (3.0 %)	11.44
2022	– 169.18	2959 (33.8 %)	66.83
2023	– 19.21	492 (5.6%)	12.13

C. *Distortions in clawback years on the intraday market*

Next, we analyze distortions in clawback years on the intraday market, starting with a fixed clawback. We find that the share of problematic quarter hours on the intraday market is much lower than on the day-ahead market. This stems from the fact that in addition to the intraday price being lower than the clawback, for condition (5) to hold the day-ahead price must be greater than the clawback (see Figure 3).

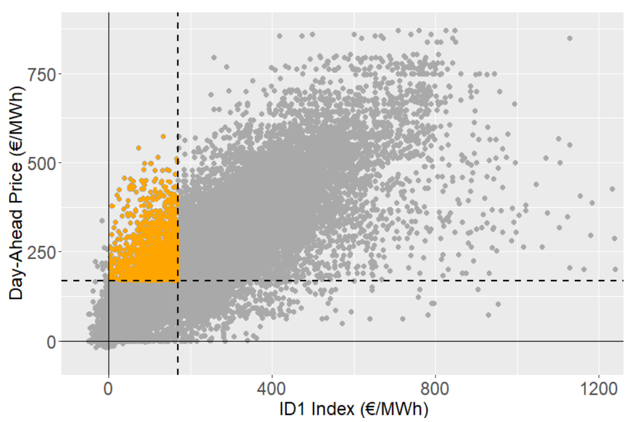

Figure 3. Distortions on the intraday market in 2022 with fixed clawback.

Table IV shows that on average the intraday price was about 37 €/MWh lower than the clawback in problematic quarter hours. This indicates that there would have been some room for the intraday price to increase due to RE generators fulfilling their obligations on the day-ahead market.

TABLE IV. DISTORTIONS IN CLAWBACK YEARS ON THE INTRADAY MARKET

Year	Payment (€/MWh)	Problematic quarter hours	Clawback type	Ø Spread ID-CB (€/MWh)
2021	– 20.59	673 (1.9 %)	fixed	8.91
2022	– 169.18	3013 (8.6 %)	fixed	36.95
2023	– 19.21	872 (2.5 %)	fixed	9.93

Lastly, we analyze the effect of introducing a dynamic clawback as defined in Eq. (4). Table V summarizes the results and shows the unweighted mean of the dynamic clawback over all hours of the year. In all three years, the average dynamic clawback is reduced relative to a fixed annual clawback. However, only in 2022 this effect is pronounced (compare with payment in Table IV). By definition, there are no hours with problematic incentives on the day-ahead market under a dynamic clawback design. On the intraday market, a dynamic clawback leads to a larger number of problematic quarter hours compared to a fixed clawback. This is due to two contrary effects. First, the condition on the day-ahead price is relaxed (it only has to be greater than zero), which increases the number of quarter hours where condition (6) holds. Second, the condition on the level of the intraday price becomes more restrictive in hours in which the clawback is adjusted to low day-ahead prices. However, hours where the clawback needs to be adjusted are likely to have low intraday prices as well due to the correlation of both markets to the underlying electricity supply and demand, e.g. due to high RE feed-in or little load. Therefore, the first effect outweighs the second and there is a higher frequency of distortions overall (see Figure 4).

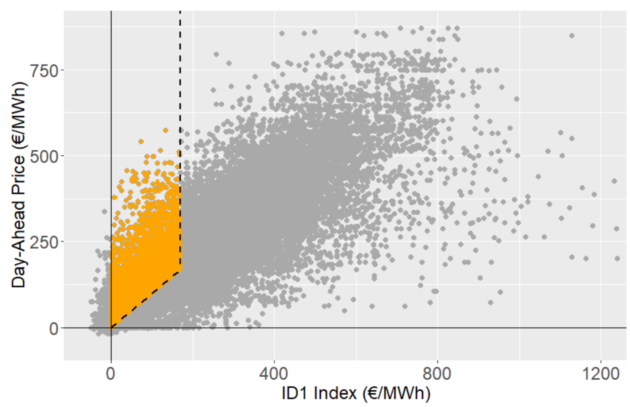

Figure 4. Distortions on the intraday market in 2022 with a dynamic clawback.

To summarize, our results show that the frequency and magnitude of distortions chiefly depend on the size of the annual support payment or clawback. The higher the payment, the more problematic incentives there are. For the observed time period 2020-2024, most of the distortions under production-based CfDs would arise in clawback years with very high prices. While the largest number of problematic incentives occur on the day-ahead market, these can be addressed by introducing a dynamic clawback. However, a dynamic clawback design shifts part of the problematic incentives to the intraday market. Distortions in support years, which are already relevant today under one-sided sliding premium schemes, were less frequent in the observed time period.

TABLE V. DISTORTIONS IN CLAWBACK YEARS ON THE INTRADAY MARKET WITH DYNAMIC CLAWBACK

Year	Ø Payment (€/MWh)	Problematic quarter hours	Clawback type	Ø Spread ID-CB (€/MWh)
2021	– 19.9	791 (2.3 %)	dynamic	8.57
2022	– 145.15	8057 (23.0 %)	dynamic	33.74
2023	– 17.81	1119 (3.2 %)	dynamic	8.99

IV. Discussion

Our results show that distorted dispatch and bidding incentives under production-based CfDs are a relevant problem given historic spot market prices and strike prices of utility-scale PV plants. This analysis gives a first indication of the relevance of these distortions in quantitative terms, although several issues limit the significance of our results.

First, we analyze a hypothetical situation in which there are production-based CfDs based on historical data that originated under different circumstances. Importantly, strike prices of PV plants would likely have been higher under a two-way CfD scheme, because producers price in the risk of being subject to a clawback obligation in high-price years. To address this limitation, an ex-ante analysis using for example an agent-based model that incorporates bidding strategies under different CfD designs may be useful. In addition, an ex-ante analysis using scenarios of the future electricity system and resulting market prices may inform about the significance of distortions in the future, which may differ from today's situation. This would complement our approach, which has the advantage of being based on real observed prices rather than uncertain price scenarios. If production-based CfDs are introduced on a wider basis, this opens up new possibilities for the ex-post analysis and evaluation of their effects.

Second, our analysis of electricity markets is static, taking market prices during a particular quarter hour as given. In reality, market prices behave dynamically and are influenced by producers' behavior, thereby limiting arbitrage opportunities to only part of the market participants. For instance, if RE producers fulfil their obligations on the day-ahead market by buying electricity on the intraday market, the ID1 index will go up until it is no longer profitable to do so. We consider this effect by analyzing the traded volume corresponding to quarter hours with problematic incentives. In an ex-ante analysis, this effect could be considered more explicitly by using a bottom-up electricity market model.

A limitation common to ex-post and ex-ante approaches alike is that the existence of problematic incentives constitutes no conclusive evidence of whether producers actually behave in a problematic way. Importantly, RE generators incur transaction costs for curtailing their plants and buying electricity on the intraday market. Providing direct evidence of problematic behavior would require sensitive data on individual plants feed-in and bidding on electricity markets, which is only available to TSOs and power exchanges. Indirect evidence might be obtained by examining aggregated data on feed-in and bidding curves of RE. If production-based CfDs are introduced despite their inability to provide undistorted incentives, particularly on the intraday market, additional 'fixes' in their design may be considered.

For this analysis, we make several simplifying assumptions that could be relaxed in principle. First, we assume that generators have zero variable cost and thus have an incentive to curtail their plants if the day-ahead price is marginally lower than the clawback. To account for small non-zero variable costs of generation or curtailment, one may define the dynamic clawback as the day-ahead prices minus a small positive amount, such as 5 €/MWh. Second, we implicitly assume that producers know the size of the support payment precisely at all times of the year. When the support payment is determined ex-post, which is common practice and desirable from an incentive perspective, the size of the support payment or clawback only becomes somewhat foreseeable towards the end of the year for an annual reference period. Thus, RE producers form expectations about the size of the support payment and must make their dispatch decisions under uncertainty, which is likely to reduce the significance of distortions, especially during the beginning of the year.

Finally, comparing the traded intraday volume with the average feed-in of PV plants is only a rough estimate for the magnitude of distortions. On the one hand, the traded intraday volumes are cumulated across all technologies, meaning that less volume is 'available' for PV plants. On the other hand, the average feed-in of PV plants also includes small-scale rooftop PV, which account for a large share of electricity generation, thereby underestimating the share of traded volumes on the intraday market.

With these limitations in mind, our analysis signifies an important step forward in informing current policy discussions around CfD designs by means of quantitative analysis rather than largely being based on qualitative arguments.

V. Conclusions

We have analyzed the significance of potential distortions under production-based CfDs on the German day-ahead and intraday markets. We find that most of the distortions under production-based CfDs would arise in clawback years with very high electricity prices. Our results suggest that a dynamic clawback design can address distortions on the day-ahead market, where the largest number of hours with problematic incentives occurs, but may exacerbate distortions on the intraday market. Distortions in support years, which are already relevant today, occur less frequent relative to distortions in clawback years.

Further research is needed to assess the relevance of distortions arising from production-based CfDs in future electricity markets to decide whether the design benefits of production-independent CfDs outweigh their implementation challenges. We suggest expanding the approach presented in this paper by analyzing traded volumes in depth and by additional data once two-way CfDs become more widespread. Lastly, ex-post analyses should be complemented by bottom-up, model-based ex-ante analysis to gauge future effects.

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APPENDIX

TABLE VI. DISTORTIONS ON THE INTRADAY MARKET IN SUPPORT YEARS WITH DIFFERENT STRIKE PRICES

Year	Strike price	Market value PV	Ø Payment (€/MWh)	Problematic quarter hours	Ø Spread (€/MWh)	Ø Traded ID1 Volume (MWh)
2020	51.34	24.58	26.76	1002 (2.9 %)	17.78	243.67
2020	75	24.58	50.42	1211 (3.4 %)	37.41	249.19
2020	100	24.58	75.42	1296 (3.7 %)	60.06	253.01
2020	150	24.58	125.42	1308 (3.7 %)	109.53	253.72

TABLE VII. FREQUENCY OF DAY-AHEAD DISTORTIONS IN CLAWBACK YEARS WITH MONTHLY REFERENCE PERIOD

Year	Payment (€/MWh)	Problematic hours	Ø Spread (€/MWh)
2021	[– 215.82, 13.88]	666 (7.6 %)	140.22
2022	[– 345.22, – 64.83]	1754 (20.0 %)	95.93
2023	[–70.64, 1.06]	868 (9.9 %)	6.80