IET Renewable Power Generation

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The Institution of Engineering and Technology

ORIGINAL RESEARCH OPEN ACCESS

Development of a Pricing Model for the Reactive Power Supply via Statcom Capability of a Real PV Power Plant

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Received: 8 July 2024 | **Revised:** 19 May 2025 | **Accepted:** 20 June 2025

Funding: Bundesministerium für Wirtschaft und Klimaschutz and 50Hertz Transmission GmbH.

ABSTRACT

The German Energiewende policy mandates the gradual decommissioning of conventional power plants, shifting the responsibility of reactive power (Q) provision to renewable energy sources. This paper evaluates the economic benefits and impact on inverter lifespan of extended Q provision, developing a pricing model that considers both dispatch and reserve costs. The study examines the provision of Q outside the technical connection rules of a utility-scale PV power plant in the transmission grid. Utilizing a detailed simulation model of a real extra high voltage PV park with 350 MW installed power, cost components are presented, valuation approaches formulated, and their application in the transmission grid examined. The basic valuation approach considers both plant-specific and external costs, focusing on active power losses and inverter wear. The analysis shows that relative losses (MWh/Mvar) in the park vary due to dispatch patterns, representing the highest cost sensitivity. Our results underscore the importance of these factors in determining the Q price. The findings indicate that additional Q can be provided without structural changes to the inverters, but economic viability depends on appropriate compensation mechanisms. A field study investigation of the simulative observation is recommended for further validation and is done in the research project Q-REAL.

1 | Introduction

Following the German government's decision to implement the Energiewende, conventional power plants are being gradually decommissioned, with coal power plants scheduled for complete shutdown by 2038 [1]. This decommissioning is being offset by an increase in the number of renewable energy sources (RES), which must now take on new roles traditionally filled by conventional power plants. One critical role is the provision of reactive power, essential for maintaining voltage stability and overall grid reliability.

In Germany, the demand for reactive power has continued to rise in recent years. This is due to the greater transport distances for electrical power from the generation centres in the north to the load centres in the south of Germany, the higher degree of cabling, and the higher grid utilization. At the same time, the demand for reactive power is becoming more dynamic overall. A particular challenge is that reactive power cannot be transmitted over long distances economically and must therefore be provided locally [2, 3]. All of this leads to many challenges in reactive power management.

In the Network Development Plan Electricity 2037/2045 of the German Transmission System Operators (TSOs), significant additional reactive power demands have been identified. By 2030, there may be instances where, during certain hours, the conceptually designed fault clearance can no longer be reliably ensured. Therefore, already planned measures for reactive power management must be advanced, and additional sources must be developed [4].

Historically, conventional power plants have provided and continue to provide a significant share of the reactive power demand of the grid. However, as these plants are phased out, reactive power provision will rely more on small-scale sources, such as fully integrated network components (FINC) owned by the individual TSOs, remaining power plants, and RES.

In particular, RES can play a major role in the provision of reactive power, as a significant proportion of them are connected to the grid via flexibly controllable inverters. However, their reactive power provision is currently constrained by the German Technical Connection Rules (TCR), which impose defined operational limits.

A key restriction of the TCR is that RES are not required to provide any reactive power when their active power feed-in is low or zero (see Section 2.1). This regulatory constraint prevents RES from delivering reactive power continuously (24/7), representing one of the major barriers to their full integration into reactive power management [5]. However, for most inverters, especially PV inverter, it is technically possible to provide additional reactive power outside of these mandatory TCR ranges without structural modifications or oversizing the converters, even during periods of low or no active power feed-in [6, 7]. This ability, commonly referred to as STATCOM functionality, allows RES to support reactive power independently of the active power feed-in.

Recent regulatory developments in Germany aim to address these limitations through two key measures. First, discussions are ongoing within regulatory bodies to expand the permissible operating ranges of RES, including the potential utilization of their STATCOM functionality. Second, a new reactive power market has been introduced to enable a market-based procurement of reactive power (see Section 3). The implementation of this market is expected to create economic incentives for the provision of reactive power from RES and facilitate a cost-efficient and flexible procurement process. However, as the market is newly introduced, there are currently no empirical data on price developments, and the first market-based procurements are not expected to take place until early to mid-2025 [8].

Moreover, there are still significant uncertainties regarding the economic viability of extended reactive power provision from RES, particularly photovoltaic (PV) and wind parks. One major concern and object of investigation is the negative impact of extended reactive power provision on the lifespan of the electrical equipment within the park, particularly the inverter [9–12].

Against this background, this paper contributes to the discussion on integrating RES into reactive power management by addressing two fundamental aspects: (1) the technical capabilities and regulatory challenges of RES-based reactive power provision, and (2) the economic implications of extended reactive power operation including potential wear effects on hardware and associated operational costs. In addition to the theoretical analysis, the findings are applied to a real extra high voltage (EHV) PV park with an installed capacity of approximately 350 MW. This PV park has been identified as a potential reactive power provider and is expected to be utilized for extended reactive power provision in the future. The insights gained in this study are applied to this real-world case to obtain practical experience and validate the theoretical findings.

The remainder of this paper is structured as follows: Section 2 examines the technical aspects of reactive power provision from RES, including regulatory requirements and operational constraints. Section 3 describes the design and structure of the German reactive power market, outlines the current status, and provides an outlook on future developments. Section 4 explores the technical challenges and potential implications of extended reactive power provision on inverter lifespan, with a focus on wear mechanisms and expected degradation effects. Section 5 describes the PV park, the simulation model, and the loss calculation and allocation. Section 6 presents different operating scenarios for reactive power provision of the real PV park, developed in collaboration with German TSO 50Hertz. The findings of the previous chapters are then used in Section 7 to identify and quantify relevant parameters for designing a pricing model. The developed pricing model is then applied to the specific case of the real PV park in Section 8, where the costs of extended reactive power provision for this particular case study are quantified. Finally, Section 9 summarizes the key findings, discusses their implications, and provides conclusions on the economic feasibility of extended reactive power provision from RES.

This article analyzes the main factors influencing the economic efficiency of extended reactive power provision using a real PV park, including a detailed examination of the potential economic benefits, the impact on the lifetime of the systems, and the necessary conditions for achieving a balanced cost-benefit ratio for both system and grid operators. In this way, this paper makes an important contribution to the broader understanding of integrating renewable energy sources into the reactive power management of grid operators and supports the transition to a more sustainable and resilient energy system.

2 | Reactive Power Capability of Renewable Energy Sources and Grid Requirements

This chapter describes the regulatory requirements for the provision of reactive power by RES (Section 2.1) and the potential applications of RES in the context of reactive power management by network operators (Section 2.2).

2.1 | Grid Requirements for RES

In Germany, RES are required by technical regulations to provide a certain level of reactive power capability. To this end, dedicated committees have defined the so-called Technical Connection Rules (TCR). Based on these regulations, grid operators establish their own Technical Connection Conditions, which apply specifically to their respective grid regions. These conditions are part of the individual grid connection agreements that govern the requirements for grid-connected generation units. The applicable TCR depends on the voltage level at which the plant is connected.

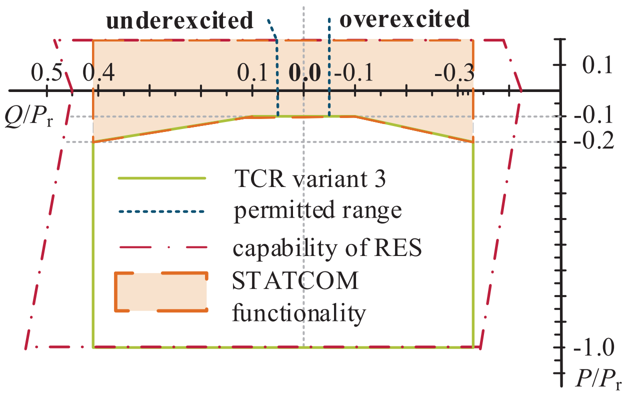

FIGURE 1 | Schematic representation of the reactive power ranges as a function of active power feed-in. Based on [17].

Consequently, the permissible reactive power operating ranges and operational modes are also defined as follows:

- **Extra High Voltage (EHV) and High Voltage (HV)**: At the grid connection point (GCP), the grid operator can select from three predefined variants for the reactive power capability. These variants differ in terms of their maximum underexcited and overexcited reactive power capability. This allows the grid operator to take into account the specific reactive power requirements in the grid region (e.g., by selecting a variant with a larger underexcited range). The applicable technical connection rule is TCR 4130 for EHV [13] and TCR 4120 for HV [14].
- **Medium Voltage (MV)**: Only one symmetric variant is available, which has equal limits for underexcited and overexcited reactive power. The applicable regulation for MV is TCR 4110 [15].
- **Low Voltage (LV)**: The specifications for reactive power capability in LV depend on both the RES connection capacity and its operational strategy. Plant operators can decide whether they want to reduce active power feed-in in favor of reactive power provision. This enables the possibility to limit active power feed-in at times of high active power generation while meeting reactive power demand. Since PV systems typically do not operate continuously at rated power, this regulation helps avoid the need for oversized inverters. The applicable regulation for LV is TCR 4105 [16].

Figure 1 shows the operating range of an exemplary RES system at the EHV level for variant 3 (maximum underexcited variant).

The minimum technical requirement of the TCR EHV 4130 [13] is depicted in green in Figure 1. As can be seen, RES at the EHV, HV, and MV levels are currently only required to provide reactive power when their active power feed-in exceeds 10% of their rated active power. Below this threshold, a permissible range (blue dotted) is defined within which RES can operate without the obligation to supply reactive power. This means that RES become systematically usable for the grid only when exceeding this feed-in threshold.

In addition, Figure 1 illustrates the technically feasible operating range of RES (red area) as well as the so-called STATCOM range (orange area). The STATCOM range represents the operating range in which RES can provide reactive power even when little or no active power is being fed in, making it particularly relevant for extended reactive power management. For PV systems, this range is also referred to as QbyNight or Q@Night.

Within the defined TCR limits, the grid operator has various options to actively control the reactive power provision of the RES. This is typically done by specifying a reactive power characteristic such as the volt-var characteristic (see Figure 8), or by directly setting a reactive power setpoint at the GCP, which can be adjusted according to the grid situation.

Although the $\cos\varphi(P)$ characteristic was historically used, it has become less common at the EHV and HV levels, as it adjusts reactive power provision solely based on active power feed-in, without considering the actual grid conditions. Instead, the volt-var characteristic is now more widely applied, as it dynamically responds to the current grid situation by referencing the voltage at the GCP.

2.2 | Applications for the Provision of Reactive Power from RES

The feed-in of pure active power by RES leads to an increase in voltage at the GCP. Historically, reactive power from RES has primarily been used to counteract this effect through underexcited reactive power feed-in. However, the actual impact on grid voltage strongly depends on the R/X ratio at the GCP. In practice, the purpose and possibilities of reactive power provision vary depending on the voltage level of the RES.

In general, the higher the voltage level, the lower is the influence of an individual RES on grid voltage. At the same time, with increasing voltage levels, the degrees of freedom for flexible reactive power provision increase, enabling grid support services such as the exchange of reactive power between grid operators [6]. This relationship is illustrated in Figure 2.

As seen in Figure 2, plants in the LV level are primarily used for local voltage regulation. The same applies to plants in the MV level that are located further downstream in the distribution grid. The closer an MV plant is to a substation connecting to the high voltage level, the greater its flexibility for grid-oriented reactive power provision. It is, for example, not uncommon for MV plants near the substation to the HV level to operate with a rather capacitive characteristic to partially compensate for the inductive reactive power demand of other generation units in the MV and LV grid [18]. At the HV and EHV levels, RES are particularly relevant for higher-level reactive power management, as they can be deployed more flexibly.

Despite the high potential and the controllability of HV and EHV RES, these resources are still not systematically integrated into reactive power management at the interface between the transmission and distribution grids [5]. A key reason for this lies in the current regulatory framework. As described in the previous section and illustrated in Figure 1, RES at the EHV, HV, and MV levels are currently not required to provide reactive power if their

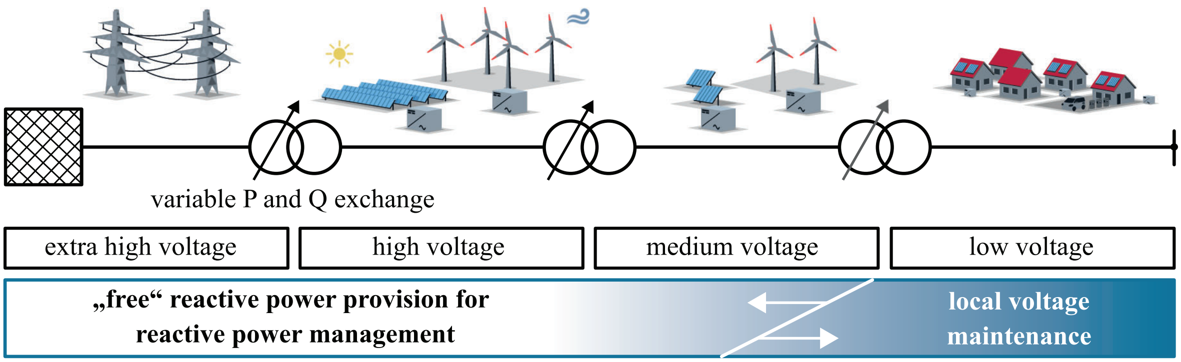

FIGURE 2 | Possible uses of reactive power from RES depending on the voltage level.

active power feed-in is below 10% of their rated active power. However, this limitation is not technically driven but rather a result of regulatory constraints.

Since most installed RES plants are connected to the grid via inverters with flexible controllability, the technical capability already exists today to provide reactive power even at low or zero active power feed-in. This is particularly true for PV plants, whose inverters are typically equipped with STATCOM functionality (see orange area in Figure 1). The utilization of the STATCOM functionality for both new and existing plants could enable 24/7 availability of reactive power from RES. This would remove one of the biggest barriers to the active integration of RES into grid reactive power management while unlocking additional, dynamic sources of reactive power for the grid.

To systematically leverage these potentials, two major measures are currently being discussed or have already been implemented in Germany:

- **Expansion of TCR-Defined Operating Ranges**: Regulatory discussions are underway regarding the expansion of TCR-defined operating ranges to allow reactive power provision even when active power feed-in falls below the current threshold of 10% of rated power. While concrete regulations have yet to be established, it is possible that RES will be required to possess the capability to supply reactive power in at least part of the STATCOM range in the future.
- **Introduction of a Reactive Power Market**: A market-based procurement system for reactive power has been approved in Germany to create economic incentives for more flexible reactive power provision (see Section 3).

3 | Market-Based Procurement of Reactive Power in Germany

This chapter outlines the essential aspects of the German reactive power market. For further details, reference is made to the decision of the Bundesnetzagentur [19] and the accompanying document [20], which provide comprehensive explanations. The Bundesnetzagentur is the German regulatory authority for power grids and other infrastructure sectors

3.1 | Background and Motivation

As previously mentioned, the increasing share of RES in the power system is driving fundamental changes in the provision of ancillary services, including reactive power supply. In Germany, the reactive power demand of TSO and Distribution System Operator (DSO) is currently met through a combination of different measures:

- **Provision According to TCR**: Reactive power can be provided by RES in accordance with the applicable Technical Connection Rules (TCR), as discussed in Section 2.1.
- **Bilateral Contracts**: Reactive power is procured via contractual agreements with individual providers. This mainly involves conventional power plants at the EHV level.
- **Use of Grid Operators' Own Equipment**: Grid operators employ their own compensation devices, so-called FINC, to meet reactive power requirements or expand their deployment as needed.
- **Vertical Reactive Power Exchange**: Reactive power is exchanged between grid operators across different voltage levels, particularly at the interface between TSOs and DSOs.

As noted earlier, with the gradual phase-out of conventional power plant capacities and the continued expansion of RES, the need to develop flexible reactive power sources has become evident. To integrate existing resources more efficiently into reactive power management and to create economic incentives for reactive power provision, Germany has decided to introduce a reactive power market. The objective is to enable non-discriminatory, market-based procurement of reactive power [20]. In doing so, Germany follows the European Directive 2019/944 [21], which mandates a competitive approach to the provision of non-frequency ancillary services.

Similar approaches have also been applied in other areas of ancillary services, such as black start capability and the procurement of inertia. With the decision [22], the Bundesnetzagentur has established the framework for market-based procurement of black start capability. In contrast, for inertia provision, a regulatory draft [23] has been published, but the formal determination process is still ongoing, with stakeholder consultations currently being conducted.

These national developments are embedded within the broader framework of the European electricity market reform, which seeks to enhance flexibility, reliability, and integration of renewable energy sources across member states. In addition to Directive 2019/944 [21], which laid the foundation for market-based procurement of non-frequency ancillary services, several new legislative measures were adopted in 2024 as part of the ongoing reform. Notably, Directive (EU) 2024/1711 and Regulation (EU) 2024/1747 strengthen the legal basis for transparent and efficient procurement processes, improve coordination between system operators, and emphasize the role of advanced inverter-based resources for voltage stability. These reforms underline the importance of non-discriminatory access to ancillary service markets and support national initiatives like the German reactive power market.

These developments in Germany are also part of a broader trend at the European level to modernize electricity markets and enhance system flexibility. In addition to Directive 2019/944 [21], which laid the groundwork for competitive procurement of non-frequency ancillary services, further regulatory steps were taken in 2024. Directive (EU) 2024/1711 [24] and Regulation (EU) 2024/1747 [25] aim to strengthen the electricity market framework in the EU, with a focus on improved market access, short-term flexibility, and fairer price signals. While they do not address reactive power provision explicitly, they reflect the overarching political goal of enabling a more efficient and responsive electricity system, which provides important context for national efforts such as the German reactive power market.

The following sections describe the regulatory framework, market design, defined reactive power products, and the current development of the reactive power market.

3.2 | Regulatory Framework and Market Design

According to the regulations of the Bundesnetzagentur, reactive power procurement in Germany follows a three-pillar model:

- **TCR Requirements and Grid Operator Coordination**: Reactive power provision through existing connection guidelines and coordinated measures among grid operators.
- **Market-Based Procurement**: Competitive bidding for reactive power demand to enhance economic efficiency and flexibility.
- **Utilization of FINC**: Use of pre-existing FINC owned by grid operators.

The legislator has mandated that market-based procurement should become the standard. Exceptions are permitted only when it can be demonstrated that market-based procurement is not economically efficient [20]. The regulation applies to TSOs and DSOs operating HV or EHV networks. Operators of medium- and low-voltage networks are exempt from market-based procurement, as local voltage regulation is the primary focus in these networks (see Section 2.2). In the case of mixed-voltage networks, only the EHV and HV sections operated by the respective grid operators are affected [20].

The market design stipulates that grid operators issue tenders for their reactive power demand, and asset operators can submit bids. Eligible participants include RES operators, decentralized generation plants, demand response units, energy storage facilities, and aggregators. A prerequisite for participation is that the assets must be connected to the grid region where the grid operator has issued the tender.

Applicants must submit a PQ diagram of their facility, indicating the available reactive power capacity at nominal voltage and the mandatory operating ranges defined by the TCR. Only operating points that exceed the mandatory TCR range are eligible for compensation. [20]

3.3 | Product Categories and Compensation

To implement market-based reactive power procurement, four standard products have been defined, as shown in Table 1. These standard products differ in terms of reactive power control mechanisms, compensation models, and whether reactive power availability and/or reactive energy provision is remunerated. The following standard products are defined:

- **Standard Product 1**: Specification of a voltage setpoint at the GCP.
- **Standard Product 2**: Reactive power control based on a predefined characteristic curve.
- **Standard Product 3**: Online specification of a reactive power setpoint.
- **Standard Product 4**: Specification of defined operating modes or schedules.

The network operator specifies the required standard product in the tendering process. Deviations from the established standard products are only permitted in justified exceptional cases, for instance, when economic or technical constraints make it necessary.

In addition to the different reactive power products, a distinction is made between secured and unsecured reactive power provision. Secured provision requires that the supplier ensures continuous availability of reactive power at the contracted level. This is for example possible for assets equipped with STATCOM functionality. Unsecured provision, on the other hand, does not require continuous availability. For example, an asset without STATCOM functionality may only be able to provide reactive power above a certain active power generation level.

Accordingly, the compensation structure differs for secured and unsecured reactive power provision:

- **Secured Provision**: Compensation for both capacity reservation (€ /Mvar) and delivered reactive energy (€ /Mvar).
- **Unsecured Provision**: Compensation only for the actual provision of reactive energy (€ /Mvar).

TABLE 1 | Overview of standard products for reactive power procurement in the German reactive power market [20].

Standard Product	Technical Description	Call-off Method	Availability	Compensation
1. Voltage setpoint	Specified voltage setpoint by grid operator	Setpoint adjustment during service period or schedule specification possible.	Secured	Capacity price + Energy price
			Unsecured	Energy price
2. Characteristic curves	Q exchange based on a predefined characteristic curve	Adjustment within service period possible	Secured	Capacity price + Energy price
			Unsecured	Energy price
3. Online setpoint	Grid operator provides online setpoint for Q exchange	Setpoint is requested online for target value	Secured	Capacity price + Energy price
			Unsecured	Energy price
4. Predefined operation mode or schedule	Grid operator specifies target and operation mode	Based on schedules (regularly transmitted) or long-term predefined operation mode	Secured	Capacity price + Energy price

3.4 | Expected Impact and Future Development

At the time of writing, the reactive power market is still in its early implementation phase. The Bundesnetzagentur mandates that grid operators must initiate at least one market-based procurement process for reactive power within 12 months of the regulation's adoption. The TSO tenders are expected by mid-2025, although some TSOs are planning to launch tenders as early as the first quarter of 2025. Within 36 months, grid operators must implement market-based procurement across all grid regions where a corresponding demand exists. [8]

The German TSO 50Hertz Transmission has already defined specific grid regions where market-based procurement for reactive power will take place [26]. Due to the novelty of the reactive power market, there is currently limited empirical data on the price development of standard products.

A key challenge in the pricing of reactive power provision is the lack of clarity regarding actual operating costs and the long-term impact on hardware components in RES plants. Particularly, the influence of increased reactive power provision on inverter lifespan remains an ongoing topic of discussion (see Section 4). This paper contributes to closing these knowledge gaps by analyzing a real-world application in collaboration with the inverter manufacturer Delta Electronics and the TSO 50Hertz. Through this practical approach, the study provides valuable insights into the economic viability of reactive power provision, helping to create a more transparent and practice-oriented pricing framework.

Overall, however, it is expected that economic incentives will encourage the participation of RES operators, and market mechanisms will enhance the efficiency of reactive power management. The introduction of a reactive power market further creates new incentives for plant operators and project developers to assess the STATCOM capability of their assets as part of the grid connection process. This could lead to increased investments in software and hardware upgrades for inverters to ensure compliance with the new market requirements and to maximize participation opportunities. In the long term, the market-based approach is expected to facilitate a more flexible and efficient use of available reactive power resources, reduce grid constraints, and improve overall system stability.

4 | Hardware Effects on the Inverter

As previously described, the additional provision of reactive power affects the wear and tear on the inverter hardware, which can have a negative impact on its lifespan and, consequently, on the economic viability of reactive power provision from RES. In the following, the identified hardware influences on this wear and tear are classified with regard to their incorporation into the pricing model. For these considerations, close collaboration was possible with the inverter manufacturer Delta Electronics, which supplies the M125HV [27] inverters used in the park.

4.1 | Humidity, Ventilation and Switches

The extended reactive power supply can have an impact on humidity, ventilation and the service life of the switches.

- **Humidity**: At night, condensation may form inside the inverter, potentially leading to failures in circuit boards or semiconductor modules. However, operating in QbyNight mode generates current flow, raising the internal temperature and thereby reducing humidity levels. This could have a positive effect on inverter hardware. Additionally, Delta Electronics specifies that the inverters used feature coated circuit boards, which enhance resistance to moisture-related damage.
- **Ventilation**: The inverter's ventilation system is designed to dissipate heat generated by current flow. Since fan operation is restricted at night due to noise regulations, extended reactive power operation does not significantly contribute to ventilation wear and tear. Furthermore, according to the manufacturer, the inverter can provide up to 60% of its rated active power as reactive power at night without requiring active ventilation.

- **Switches**: The lifespan of a switch is typically defined by the number of switching cycles, which depend on several parameters. For simplicity, it is assumed that more frequent switching accelerates wear, thereby reducing switch longevity. However, in the studied PV park, inverters normally disconnect from the grid at night. When STATCOM functionality is required, they remain connected instead, thereby eliminating one switching cycle per night. This reduction in switching frequency mitigates wear and does not negatively impact switch lifetime.

Given these considerations, humidity, ventilation, and switch wear are not included in the pricing model, as their impact on hardware degradation is negligible or even positive.

4.2 | Power Electronics

The use of STATCOM functionality also affects the power electronic components within the inverter. This study considers three factors in detail:

- Cosmic radiation
- Installed capacitors
- Semiconductor stress

Below is a brief explanation of each of these factors in order to place them in the context of the pricing model.

4.2.1 | Cosmic Radiation

The voltage stress limit of power semiconductors is critical in the context of cosmic radiation. When cosmic rays strike a semiconductor under high electric field stress (e.g., at DC link voltage), they generate a large number of charge carriers–typically in the range of tens to hundreds of MeV [28]. This can trigger a current channel, potentially leading to semiconductor failure. The failure probability of semiconductors increases with higher applied voltage and lower temperatures. This probability is typically expressed in failures in time (FIT), which denotes the number of failures per 1 billion operating hours. For example, an inverter using 12 Semikron modules exhibits the following failure rates:

- When switched off at night: FIT $\approx$ 30.75 (mean time to failure: 3712 years)
- When connected to the grid at night with DC link voltage applied: FIT $\approx$ 61.65 (mean time to failure: 1852 years)

This represents an approximate 0.5% lifetime reduction for the Delta Electronics inverter. Assuming a 20-year lifespan, this equates to a lifetime loss of about 2 months.

Due to its minimal impact, cosmic radiation is not included in the pricing model.

4.2.2 | Capacitors

Capacitors play a critical role in inverter operation, particularly in the AC filter and DC link. Since the inverter's lifetime is directly dependent on capacitor longevity [29], their degradation is an important consideration.

There are two primary capacitor technologies:

- Aluminum electrolytic capacitors
- Film capacitors

A key difference between these technologies is the aging behavior.

- Electrolytic capacitors suffer from electrolyte evaporation, a process that accelerates with temperature. A 10°C temperature increase can halve the capacitor's lifespan [30].
- Film capacitors, such as those used in the studied inverters, are made of metal-vaporized plastic films. These capacitors are less sensitive to temperature and do not suffer from aging effects.

Since the inverters in this study rely on film capacitors (used in AC filters, DC links, and auxiliary power supplies), aging effects are negligible. Therefore, capacitor degradation is not considered in the pricing model.

4.2.3 | Semiconductor

Thermal cycling is a major factor influencing semiconductor failure. In order to predict the lifetime using thermal cycling, load profiles for the inverter are required and used in this study.

In addition to normal operation within the TCR operating ranges, STATCOM functionality was also included in the load profile. Delta Electronics provided the mean time between failure (MTBF) calculation for the inverters. The MTBF can be used to estimate how many years the inverter will operate reliably under given conditions. This estimate considers a wide range of inverter components, such as MOSFETs, transistors, and diodes. The data includes MTBF values for inverter operation with and without STATCOM functionality, providing 30% (35 kvar, 0.3 pu) and 60% (70 kvar, 0.6 pu) of nominal apparent power as reactive power.

Based on these MTBF values, different reactive power supply scenarios were defined, each varying in the number of days per year in which reactive power provision occurs. For each scenario, the estimated inverter lifetime was calculated, distinguishing between half (0.3 pu) and full (0.6 pu) reactive power provision:

- **Weekend (WE)**: QbyNight used every weekend of the year.
- **Weekend + 2 Weeks (WE + 2W)**: QbyNight used every weekend + 2 additional weeks per year.
- **0.5 year**: QbyNight used for half a year.
- **Full year**: QbyNight used every night.

TABLE 2 | Lifetime loss in years and percentage for different reactive power provisioning scenarios.

Scenario	Years of loss (ΔL) in percent
30% Q WE	10.4%
60% Q WE	10.9%
30% Q WE + 2W	11.9%
60% Q WE + 2W	12.5%
30% Q 0.5 year	18.3%
60% Q 0.5 year	19.2%
30% Q full year	36.6%
60% Q full year	38.4%

WE: weekends; 2W: 2 weeks.

TABLE 3 | Calculated lifetime degradation depending on the supplied reactive energy (kvarh).

Scenario	WE	0.5 a
Calculated additional reactive energy in kvarh		
30%	1,653,028	2,873,120
60%	3,306,056	5,746,241
Lifetime loss hours in h/kvarh		
30%	0.010329252	0.010457143
60%	0.005412925	0.005485714
Scaling to total lifetime loss λ_Q in %/kvarh		
30%	0.000006291	0.000006369
60%	0.000003297	0.000003341

This results in a total of eight different scenarios for which the percentage lifetime reduction ΔL was calculated (see Table 2). For example, the scenario 30% Q WE means that the inverter provides reactive power every weekend of the year, maintaining a constant output of up to 30% of its apparent power (35 kvar). Given 2 days per week and 52 weeks per year, the inverter would supply 35 kvar of reactive power for 104 days per year. In the 60% Q WE scenario, the reactive power level changes accordingly to 70 kvar.

For each scenario, the percentage of lifetime loss of the inverter ΔL is shown in Table 2 and is calculated using the following Equation (1):

$$\Delta L = \left(1 - \frac{L_{Q,Scenario}}{L_{\mathrm{Q=0}}}\right) \cdot 100\% \tag{1}$$

where $L_{\mathrm{Q=0}}$ indicates the calculated lifetime for the inverter in the case where no reactive power is provided. $L_{Q,Scenario}$ represents the calculated lifetime of the inverter for the specific Q feed-in scenario.

The data show a non-linear relationship between increased Q supply and lifetime reduction. Even when the reactive power provision doubles (from 30% to 60%), the additional lifetime reduction remains relatively low, ranging between 0.5 and 1.8 percentage points. This suggests that the basic activation of QbyNight has a much stronger impact on lifetime reduction than the exact level of reactive power supplied.

To quantify the economic impact, the next step is to calculate the lifetime loss per kvarh of reactive power supplied, see Table 3. This involves:

- Determining the total additional reactive energy (kvarh) supplied in each scenario.
- Relate the calculated lifetime loss to this additional energy, resulting in lifetime loss per kvarh.
- Normalize the values to the total lifetime of the inverter to obtain a comparative metric.

The complete formula for the calculation is shown in the following equation (2).

$$\lambda_Q = \frac{1}{E_{\mathrm{Q,Scenario}}} \cdot \frac{\Delta L \cdot L_{\mathrm{Q,Scenario}}}{L_{\mathrm{Q=0}}} \cdot 100\% \tag{2}$$

where λ_Q represents the total percentage of inverter lifetime loss per kvarh of reactive power fed in. $E_{\mathrm{Q,Scenario}}$ denotes the total reactive energy supplied over the inverter's lifetime for the respective scenario.

To quantify the impact of additional reactive power provision on inverter lifetime, the calculated lifetime reduction values are first averaged and then related to the total supplied reactive power. This allows for a precise estimation of wear per unit of reactive energy. When the inverter provides 30% of its nominal apparent power as reactive power at night, each Mvarh of reactive power leads to an average lifetime reduction of 0.0062915%. When operating at 60% reactive power provision, the corresponding reduction is 0.0032970% per Mvarh. The mean value of these two scenarios is 0.0047942% per Mvarh, providing a general estimate of lifetime degradation due to night-time reactive power provision.

For better understanding, the percentage wear costs are applied to an example inverter with a purchase price of € 7,000. Two different approaches can be considered within a pricing model. The first approach divides the operating range of the PV park into two segments: 0 to 35 kvar (0 to 0.3 pu) and 35 to 70 kvar (0.3 to 0.6 pu). Different prices are set for each range based on the previous considerations. This reflects that the most significant aging process occurs primarily in the 0 to 0.3 pu range, and in the 0.3 to 0.6 pu range, the aging and consequently the price increase only slightly. Specifically, the two estimated values are 0.44 € /Mvarh for 0-35 kvar and 0.23 € /Mvarh for 35-70 kvar. The second approach uses the average value of 0.34 € /Mvarh for all reactive power demand scenarios, representing a single average price across the entire range. These approaches are shown in Figure 3.

Based on the estimates calculated above, the impact of semiconductor lifetime loss due to additional reactive power requests is considered in the pricing model.

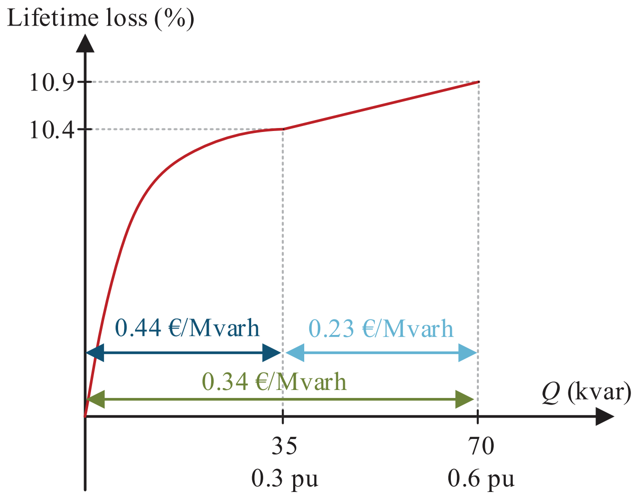

FIGURE 3 | Possibility for the pricing of different reactive power requests.

5 | PV Power Plant and Simulation Model

The investigations presented in this paper are based on a detailed simulation model of a real PV park connected to the extra high voltage (EHV) grid, with an installed capacity of approximately 350 MW. The PV park is expected to provide reactive power even during times when little to no active power is being fed in, in anticipation of the upcoming German reactive power market. This chapter first explains the structure of the PV park, its reactive power capabilities, and the basic reactive power control implemented in the park. Subsequently, the calculation and allocation of losses, which have a significant impact on the economic viability of the extended reactive power provision, are detailed. Finally, the entire operating range of the park is analyzed concerning the reactive power behavior and the losses.

5.1 | Description of the PV Power Plant

The PV park under investigation was connected to the grid of the German TSO 50Hertz in the second quarter of 2024. As described initially, the PV park has an installed active power capacity of 350 MW. Due to mandatory requirements of the German TCR for EHV [13], this corresponds to an apparent power capacity of approximately 390 MVA. This power is connected to the EHV grid through two extra high voltage/medium-voltage transformers and is distributed across 2785 inverters of the type M125HV from Delta Electronics [27]. The inverters have a nominal active power capacity of 125 kW or, respectively, 140 kVA apparent power. These inverters are by default equipped with STATCOM functionality and can provide reactive power in a range from −0.75 pu to 0.75 pu. However, the maximum reactive power provision is reduced to 0.41 pu during periods of high active power feed-in. This reduction occurs because the inverters are designed to handle only these values at maximum active power output according to the TCR EHV variant 3.

Despite the relatively large control range of the inverters, the park achieves smaller reactive power control ranges at the GCP, see red area in Figure 1. This is partly due to the park's own reactive power demand, which ranges from −4.2 Mvar in no-load conditions to 52.3 Mvar at full active power feed-in (see Section 5.5, Figure 5). In addition to this technical limit, the park's operating range is further restricted to avoid active cooling of the inverters at night, thereby reducing noise emissions. Beyond the aforementioned limits, there are also operational constraints imposed by the TSO, who restricts the extended reactive power provision to the TCR-defined range (Figure 1, green) and the STATCOM range (Figure 1, orange).

The simulation model of the park is implemented in the network analysis software PowerFactory from DIgSILENT. The simulations and adjustments of the park are fully controlled via the Python API of PowerFactory. The following section describes the reactive power control within the park.

5.2 | Reactive Power Control

The reactive power requirements of the grid operator must be met at the park's GCP. Within the PV park, these requirements are distributed to individual reactive power control units, known as Q-Readers. A Q-Reader comprises between 13 and 19 individual inverters and is practically the smallest reactive power control unit in the PV park. While it is technically possible to control individual inverters, it would be highly complex and is therefore not implemented.

Each Q-Reader can be assigned its own operating point. In practice, however, the control is set so that Q-Readers receive operating points proportional to their controlled power, ensuring that all inverters are evenly loaded. This simplifies the control system as no complex measurements and control schemes are needed and ensures that each inverter experiences the same load and, ultimately, the same lifespan reduction.

However, this method can lead to higher losses, as inverters located further from the GCP also provide reactive power, increasing transmission losses due to longer cable distances. Moreover, the uniform control strategy ensures that all inverters remain connected to the grid during QbyNight operation, even if not all of them are needed. As a result, no-load losses are higher compared to a more selective control approach.

An Intelligent pre-control and estimation of the reactive power demand can reduce these losses by selectively shutting down individual Q-Readers. However, this can lead to a proportional overloading of individual inverter groups. An alternating activation and deactivation of Q-Readers can partially mitigate this issue. An optimized control system within the park, balancing lower operating costs with reduced inverter lifespan, would be ideal.

Although this is not currently implemented in the park's control system, it is technically feasible. For the following investigations, a uniform distribution of operating points, as currently implemented in the park, is assumed.

5.3 | Calculation of Losses

The losses within the park can be mainly divided into transformer losses, line losses, and inverter losses. The losses in the lines and transformers are calculated using PowerFactory. For the inverter losses, the loss-based efficiency model (LEM) from [31] is used, which extends the Schmidt–Sauer model [32].

In both models, the necessary parameters are derived through measurements on the inverter. While the Schmidt–Sauer model parameters are determined under pure active power feed-in, the LEM also measures operating points where reactive power is provided. This increases the model's accuracy in these operating areas. For this study, the M125HV inverters were fully measured according to [31]. However, the specific model parameters are confidential and cannot be published here. By summing the transformer, line, and inverter losses, the total losses of the park are determined.

Although the park is primarily designed to feed in active power to the grid, for the analysis of the losses and costs for the extended reactive power provision, the calculation of the reactive power-specific additional losses P_{Loss_Q} is crucial, as they specifically arise from the provision of reactive power.

To calculate these, two simulations are conducted for each operating point. First, the losses $P_{\mathrm{Loss}_{\mathrm{Ref}}}$ for the reference case are calculated. In the reference case, the generators feed in active power according to the predefined characteristic for the active power feed-in (see Section 6), while the reactive power feed-in of the generators is set to zero, see Equation (3).

$$P_{\mathrm{Loss}_{\mathrm{Ref}}} = P_{\mathrm{Loss}}(P_{\mathrm{Gen}} = P_{\mathrm{Gen}}, Q_{\mathrm{Gen}} = 0) \tag{3}$$

With the active and the reactive power feed-in of the generators P_{Gen} and Q_{Gen}. According to the active and reactive power losses within the park, the values P_{GCP} and Q_{GCP} result at the GCP.

As a second step, a simulation is conducted to calculate the losses $P_{\mathrm{Loss}_{\mathrm{Set}}}$ for the current active power operating point and the setpoint for reactive power, see Equation (4). This is called the setpoint case.

$$P_{\mathrm{Loss}_{\mathrm{Set}}} = P_{\mathrm{Loss}}(P_{\mathrm{Gen}} = P_{\mathrm{Gen}}, Q_{\mathrm{Gen}} = Q_{\mathrm{Set}} + Q_{\mathrm{Loss}}) \tag{4}$$

The reactive power feed-in of the generators Q_{Gen} is set to $Q_{\mathrm{Set}} + Q_{\mathrm{Loss}}$ to cover the reactive power losses Q_{Loss} within the park. Similarly to the reference case, at the GCP, the values P_{GCP} and Q_{GCP} result according to the losses within the park. P_{GCP} differs from the reference case due to the reactive power-specific additional losses. For Q_{GCP}, the relationship is given by $Q_{\mathrm{GCP}} = Q_{\mathrm{Set}}$.

Finally, the reactive power-specific additional losses P_{Loss_Q} are calculated by taking the difference of the losses for the reference and setpoint cases as per Equation (5).

$$P_{\mathrm{Loss}_Q} = P_{\mathrm{Loss}_{\mathrm{Set}}} - P_{\mathrm{Loss}_{\mathrm{Ref}}} \tag{5}$$

5.4 | Allocation of Losses

For pricing, the losses calculated in Section 5.3 must then be properly allocated. The allocation of losses significantly impacts the economic viability of the park. If the operating ranges are limited to the STATCOM and TCR operating ranges (see Figure 1), three cases can be distinguished in the allocation:

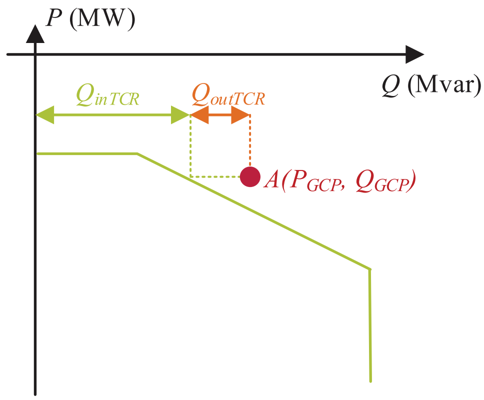

FIGURE 4 | Illustration of the exemplary allocation of the additional reactive power-specific losses for an operating point A outside the TCR with P_{GCP} between 10% and 20% of the rated power.

- Operating point A is within the TCR operating range: No consideration in pricing.
- Active power feed-in of operating point A is between 10% and 20% of the rated active power: Proportionate consideration in pricing.
- Active power feed-in of operating point A is below 10% of the rated active power: Full consideration in pricing.

According to current TCR regulations, the PV park must be able to provide reactive power within the TCR operating ranges shown in Figure 1 (green). Losses incurred within these ranges remain with the power plant operator and are not considered in this study. Nonetheless, these losses are relevant for the plant operator. Furthermore, it may be that plants providing additional reactive power through the reactive power market are also more closely integrated into the reactive power management of the grid operators. This could potentially lead to the plants providing more reactive power even within the TCR ranges, resulting in higher losses.

For operating points beyond the TCR regulations, the additional losses must be considered in the pricing. As the systems do not have to provide any reactive power below the 10% limit, the additional losses are fully considered in the pricing. Between 10% and 20%, however, the losses are divided into portions incurred by providing reactive power within and outside the TCR operating ranges. Figure 4 shows an exemplary operating point A with P_{GCP} and Q_{GCP}.

First, for the calculation of additional losses, the minimum and maximum permissible reactive power ($Q_{\min}$ and $Q_{\max}$) defined by the TCR for the current active power operating point of the park (P_{GCP}) are determined. Based on these values, the range of reactive power within the TCR limits ($Q_{\mathrm{in\ TCR}}$) is calculated.

Next, the total power losses are computed for two distinct operating points:

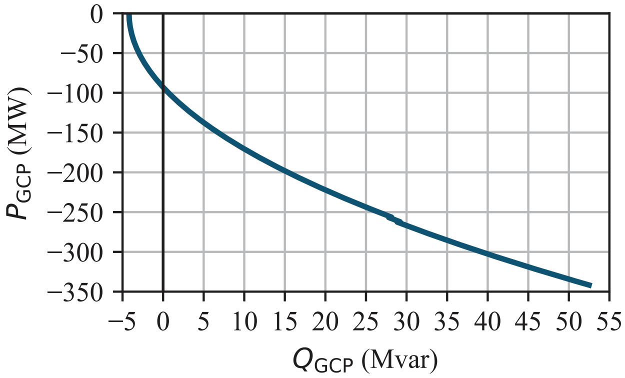

FIGURE 5 | Active and reactive power behavior of the park at the GCP with only active power feed-in from the generators.

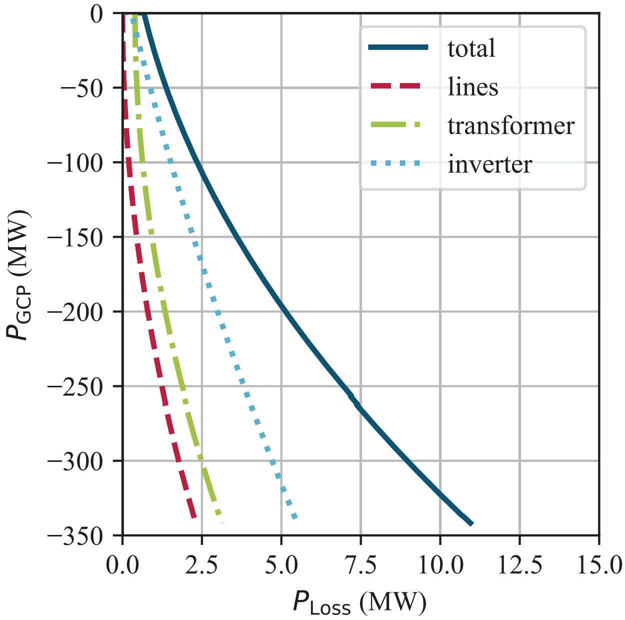

FIGURE 6 | Total losses and breakdown of losses into line, transformer, and inverter components for the park with solely active power feed-in from the generators.

- **Operating Point A1** $(P_{\mathrm{GCP}}, Q_{\mathrm{GCP}})$: Represents the current active power feed-in and the actual reactive power setpoint.
- **Operating Point A2** $(P_{\mathrm{GCP}}, Q_{\mathrm{in\,TCR}})$: Represents the same active power feed-in but with the minimum or maximum reactive power allowed within the TCR range.

Finally, the difference between the power losses at A1 and A2 is calculated. This difference quantifies the additional losses caused by providing reactive power beyond the TCR limits, as described by Equation (6).

$$\begin{aligned} P_{\mathrm{Loss_Q}} &= P_{\mathrm{Loss_{A1}}}(P_{\mathrm{GCP}}, Q_{\mathrm{GCP}}) \\ &\quad - P_{\mathrm{Loss_{A2}}}(P_{\mathrm{GCP}}, Q_{\mathrm{inTCR}}) \end{aligned} \tag{6}$$

5.5 | Operating Range Analysis

In this chapter, the park is analyzed with regard to its reactive power behavior and the losses occurring within the park. Initially, the behavior of the park is investigated when the inverters only feed in active power. This allows the estimation of the park's reactive power behavior and is important for interpreting the losses. Figure 5 shows the reactive power demand of the park at the GCP with solely active power feed-in.

The park initially shows an overexcited behavior (negative sign) due to the capacitive nature of the lines under low load. When the active power feed-in exceeds approximately 100 MW, the park increasingly exhibits an underexcited behavior (positive sign), caused by the inductive nature of the lines and transformers under higher load (see, e.g., [6]). Overall, the reactive power demand ranges from approximately −4.2 Mvar (overexcited) to about 52.3 Mvar (underexcited).

Figure 6 shows the losses in the park for the case of solely active power feed-in, broken down into the different loss components.

The inverters account for approximately 50% of the total losses within the park. The remaining losses are roughly equally distributed between transformers and lines. This ratio is consistent across the examined operating range (STATCOM + TCR), except at very low active and reactive power feed-in, where transformers contribute the most to the losses. It is important to note that the park has relatively short line lengths (see Section 5.1). In parks with longer lines, line losses can constitute a significantly higher proportion of the total losses.

The losses across the entire operating range are analyzed using an operating point analysis, in which the active and reactive power are successively varied in 0.1% increments. It is assumed that all generators feed in evenly according to the implemented Q control strategy (see Section 5.2). Figure 7 shows the total losses P_{Loss} (a) and the reactive power-specific additional losses $P_{\mathrm{Loss_Q}}$ (b), calculated according to Section 5.3, over the entire operating range. For better context, the TCR operating range applicable to the park is highlighted in green.

The total losses (Figure 7a) increase approximately quadratically with the load and reach about 12 MW, which represents roughly 3.5% of the park's rated power. The reactive power-specific additional losses (Figure 7,b) range from approximately −0.5 MW to 2.5 MW. In certain areas of the park, negative values can occur, meaning that reactive power feed-in can slightly reduce the losses within the park compared to no reactive power feed-in. The negative areas in Figure 7 are slightly stepped and do not form a continuous area, which is due to the voltage regulation of the park transformers. The stepping of the transformers is clearly visible at 250 MW.

Figure 7 also shows that the reactive power-specific losses are not symmetric about the *y*-axis but are slightly different. Within the STATCOM range, it is observed that the additional losses in the overexcited range (negative sign) are lower than those in the underexcited range (positive sign).

This asymmetry arises primarily from two factors. First, an overexcited operation of the inverters increases the voltage within the park, thereby reducing the current flow and, consequently,

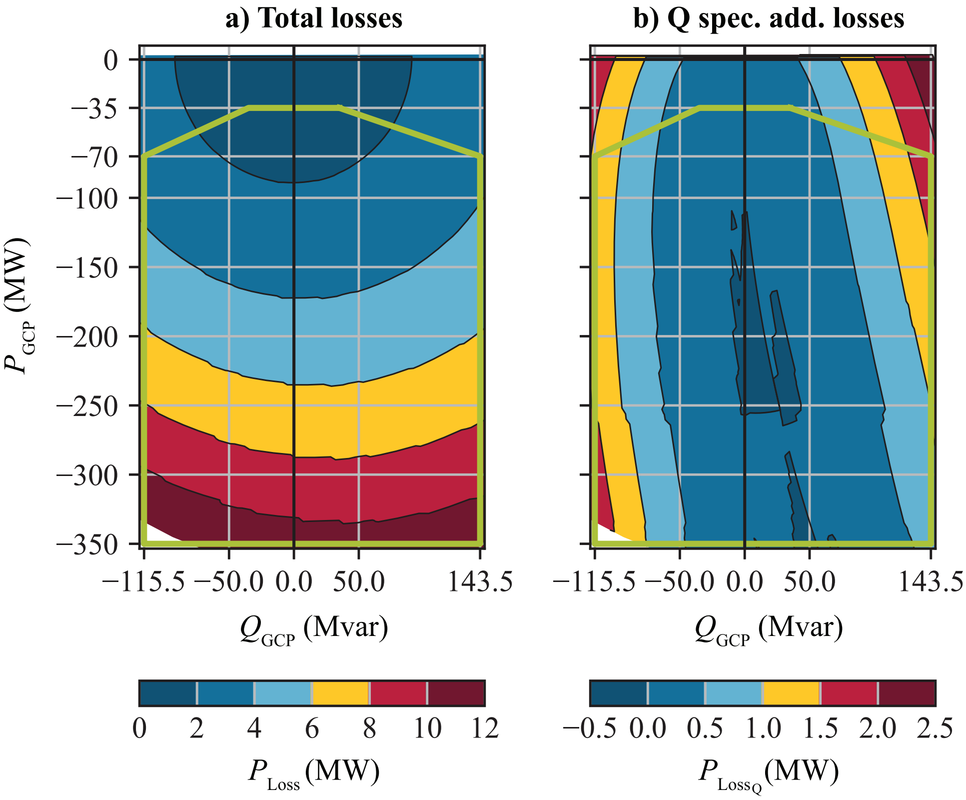

FIGURE 7 | PQ diagram with colormap showing: (a) Total losses P_{Loss} and (b) reactive power-specific additional losses P_{Loss_Q} across the entire operating range of the park.

the associated losses. Second, the generators must also provide the reactive power demand of the park equipment at the given load level. In the STATCOM range, the park predominantly exhibits overexcited behavior due to the characteristics of its internal power lines (see Figure 5). As a result, when underexcited reactive power setpoints are required within the STATCOM range, this capacitive behavior must be compensated, necessitating a higher reactive power provision to achieve the target setpoint. This, in turn, leads to increased losses. The extent of this effect is mainly influenced by the length of the internal power lines within the park. The PV park analyzed in this study has relatively short internal line lengths, which limits the impact of this phenomenon.

At high active power feed-in, this effect reverses. As the active power feed-in rises, the park exhibits an increasingly underexcited behavior (see Figure 5). To provide overexcited reactive power in this condition, the underexcited behavior must first be compensated. Consequently, the inverters must inject additional reactive power, leading to greater loading and higher losses.

Furthermore, it can be observed that at high active power feed-in, the park is unable to fully meet the overexcited reactive power requirements specified by the TCR (see Figures 7a and 7b, bottom left corner). This limitation also results from the park's pronounced underexcited behavior at high active power feed-in, requiring substantial overexcited reactive power to meet overexcited setpoints. However, the park does not fully reach high overexcited setpoints at a high active power feed-in, at least in the simulation. This issue can also be observed in other real-world PV and wind parks. It is important to note that these operating points are generally less significant because, due to the high active power feed-in, the voltage is already increased at the GCP. Providing overexcited reactive power would further increase the voltage, which is counterproductive.

6 | Operating Scenarios

The PV park analyzed in this paper is located in eastern Germany, within a grid area characterized by low local demand and high RES feed-in. The grids subordinate to the EHV grid are feed-in networks that integrate the generated RES power into the EHV grid, which then transmits the power to the load centers, primarily in southern Germany. This creates specific challenges and increasing reactive power demands that have been continuously rising for years.

Currently, a significant portion of reactive power in this region is still provided by large conventional power plants, which are planned to be decommissioned in the 2030s according to government plans [1]. This transition already results in a reactive power deficit at certain times, necessitating new sources to meet future demands.

Against the background of the reactive power market, the PV park is intended as a pilot project. The TSO has identified three different operating scenarios in which reactive power will be provided for the EHV grid outside the TCR requirements:

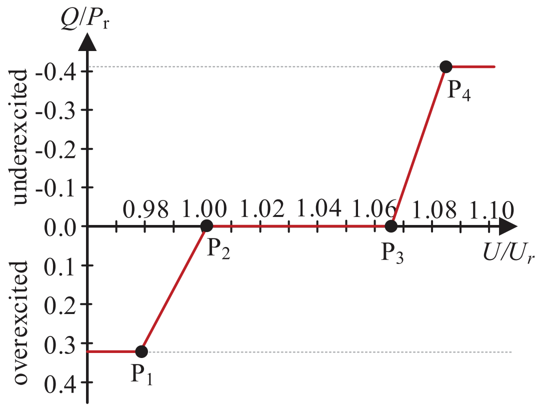

FIGURE 8 | Used volt-var characteristic according to calculate the Q setpoints for each scenario.

- **Base Scenario**: Covers weekends and holidays with low load, resulting in increased reactive power demand. The observation period is 3 days (Friday, Saturday, and Sunday). On an annual basis, this is extrapolated to weekends and holidays for an entire year.
- **Dynamic Scenario**: Represents dynamic, rapid voltage dips with prior notice, which can be caused by typical active power dips. The observation period is 24 h.
- **Extreme Scenario**: Covers periods with very high reactive power demand, for example, during maintenance shutdowns of conventional power plant units. The observation period is 3 days per year.

Two of the three scenarios are defined by a loss of reactive power potential due to the unavailability of conventional power plants. The scenarios differ in duration and the amount of reactive power demand. For each scenario, the TSO has provided historical voltage time series from a nearby substation. From these, the reactive power setpoints for the PV park are derived using the volt-var characteristic shown in Figure 8.

The limits for the overexcited and underexcited reactive power capacity of the characteristic curve are defined by the applicable TCR 4130 variant 3 for the park (see Figure 1). It should be noted that the volt-var characteristic is initially used here only to estimate the reactive power provision. In reality, the actual control of the plant may differ, for example, according to the defined standard products (see Section 3.3).

The active power feed-in is also estimated using historical solar irradiance data corresponding to the geographic coordinates. Since the volt-var characteristic continuously adjusts the reactive power output in response to voltage fluctuations, the actual reactive power provision varies dynamically throughout the scenarios. This ensures that the PV park actively contributes to voltage stabilization in line with grid requirements.

Figure 9 shows the corresponding voltage values and the active and reactive power feed-in for the scenarios.

As seen in the distribution curves for the voltage values (Figure 9, right), the voltages in all scenarios tend to be at the upper end

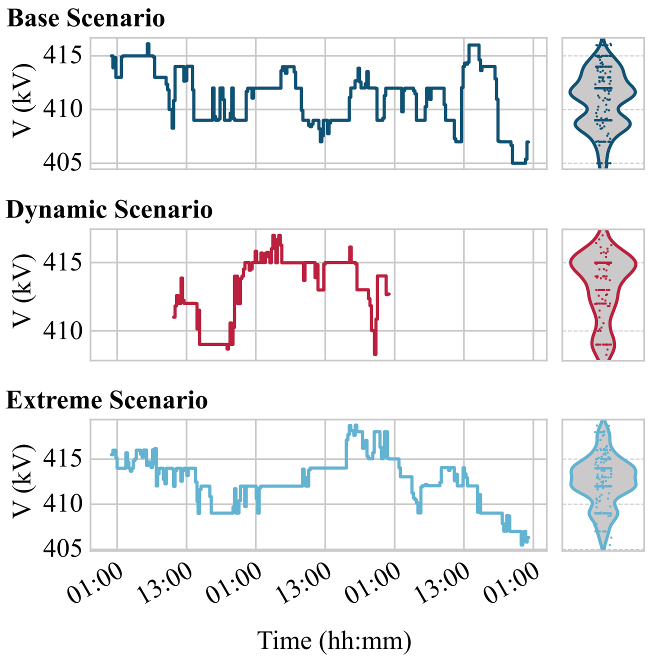

FIGURE 9 | Voltage profile at GCP for operating scenarios (blue: base; red: dynamic; light blue: extreme).

of the voltage band, typical for generator-dominated grids. It is also evident that the reactive power limit of 10% for the TCR ranges is sometimes exceeded in the scenarios. This can occur more frequently during the day due to cloud movements or other factors. To illustrate this further, the PQ diagrams for each scenario are shown in Figure 10. In addition to the P and Q values at the GCP and the required TCR range according to the TCR (green), the reactive power-specific additional losses Q_{Loss_Q} are also color-coded.

Technically, this has no impact on the reactive power potential but can have economic implications. Active participation in the reactive power market means that the power plants are likely to be more closely integrated into the grid operator's operational management and therefore used more frequently for reactive power provision. This increased utilization could also extend to the cost-free TCR ranges, affecting the economic efficiency of the plant. Therefore, it could be useful to consider this when setting prices for the additional reactive power provision.

Furthermore, it is important to note that due to the installed hardware in the PV park, activation of the park is required in preparation for potential nighttime reactive power provision (QbyNight). As a result, standby losses occur within the park during these periods. These losses must be taken into account when evaluating the overall efficiency and economic feasibility of nighttime reactive power provision. The extent of these losses depends on the park's specific inverter technology and operational strategy.

There are also inverter technologies available that allow activation of the inverter at night without requiring full system operation. By utilizing such hardware, the standby losses associated with nighttime reactive power provision could be reduced, thereby lowering the overall costs of reactive power provision.

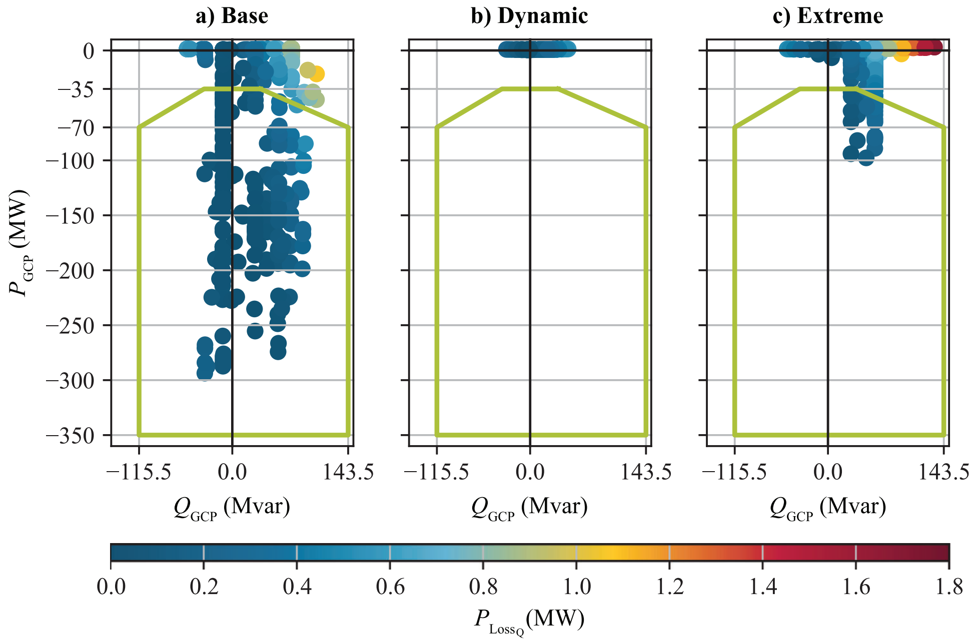

FIGURE 10 | Exemplary PQ diagrams with reactive power specific additional losses for (a) base scenario, (b) dynamic scenario and (c) extreme scenario.

7 | Pricing Model

The pricing model outlines the mechanism for calculating the price from various price components and the design of the remuneration for the extended provision of reactive power. The key components of the pricing model are described below.

7.1 | Pricing Components

The total price P_Q for the remuneration of reserved and provided reactive power outside the TCR has two relevant price components, which are taken into account: the costs for the plant operator (C_{Asset}) and the value of the reactive power for the grid operator (V_{Grid}). For the purposes of this study, V_{Grid} is replaced by a fixed incentive flat rate (F_{Grid}).

C_{Asset} includes all additional costs incurred by a plant operator for reserving and providing reactive power outside the TCR. F_{Grid} is defined as a flat rate, paid by the grid operator, as an incentive for reserving and providing reactive power outside the TCR. Several methods can be used to incorporate the relevant variables C_{Asset} and F_{Grid} into the pricing calculation. These methods are described in detail below.

7.2 | Description and Calculation of Asset-Side Costs C_{Asset}

As already mentioned, the costs on the plant side result from the additional costs of the extended reactive power supply and are divided into the provided reactive power (€ /Mvar) and the supplied reactive energy (€ /Mvarh). Based on the 2019 report "Commission on the Future Procurement of Reactive Power" [33], these costs are subdivided into:

- **Q-Capacity Costs**: Design related costs of the reserve capacity in € /Mvar.
- **Q-Reserve Costs**: Operational reserve costs in € /Mvar.
- **Q-Dispatch Costs**: Operational dispatch costs in € /Mvarh.

Q-capacity costs relate to the specific design or upgrading of a power plant to provide extended reactive power. The additional operational reserve costs include the cost of increased maintenance and repair, as well as ensuring operational readiness. Opportunity costs, additional loss costs and wear and tear costs make up the additional costs of operational dispatch. The costs relate to both reactive power and active energy losses resulting from the extended provision of reactive power.

No additional investments in reactive power capacity are required for the PV park analyzed in this study, as it is already capable of covering the extended operating range, see Section 5.1.

There are no empirical values for the additional costs of the Q reserve. Therefore, only the additional costs of operational dispatch, including additional loss and wear costs, are considered in this study. Opportunity costs can also arise if active power is supplied at the same time. This may occur, for example, during start-up and shut-down in the evening or morning hours of the plant, or when extended reactive power is required during the day. Opportunity costs are also not considered in the study as they have only a minor impact in the selected operating scenarios.

A detailed investigation of Q-capacity costs in the context of alternative investments (e.g., FINC) is recommended. Subsequently, operational experience regarding possible additional costs of Q-reserve should be derived and included in further investigations.

TABLE 4 | Total and specific costs for Q-dispatch in the different operating scenarios.

Operating scenarios	Simulated days (#d)	$C_{\text{Q-dispatch}}$ (€)	$C_{\text{specif. Q-dispatch}}$ (€)
Base	3.00	1,176.95	0.95
Dynamic	1.54	494.31	1.07
Extreme	2.99	2,843.91	0.93

After the asset side costs have been defined and determined, they are quantified below. The additional wear cost factor is formed from the acquisition costs of an inverter and the wear parameter, see Section 4. The wear parameter 4.79×10^{-5} 1/Mvarh is obtained as an average value from the previously determined wear parameters. For the additional loss costs, an average spot market price is assumed to monetise the loss energy. The average spot market price is calculated for the observation period of the operating scenarios (weekends and holidays) between 2017 and early 2020. The relevant costs for the operational use of the PV system for the extended reactive power provision are listed below.

- Additional wear costs ($C_{\text{specif. wear}}$): 0.34 € /Mvarh
- Additional loss costs ($C_{\text{specif. loss}}$): 33.51 € /MWh

The calculation of the total cost $C_{\text{Q-dispatch}}$ in Euros for the respective operating scenario results from Equations (8) and (9) below.

$$C_{\text{Q-dispatch}} = C_{\text{ttl loss}} + C_{\text{ttl wear}} \tag{7}$$

where

$$C_{\text{ttl loss}} = C_{\text{specif. loss}} \cdot E_{Loss\ \text{out. TCR}} \tag{8}$$

$$C_{\text{ttl wear}} = C_{\text{specif. wear}} \cdot E_{Q\ \text{ttl out. TCR}} \tag{9}$$

where

$E_{Loss\ \text{out. TCR}}$: Active energy losses due to reactive power provision outside the TCR in MWh

$E_{Q\ \text{ttl out. TCR}}$: Reactive energy supplied outside of the TCR in Mvarh

Equation (8) calculates the cost of the total active energy losses $C_{\text{ttl loss}}$ resulting from the extended reactive power supply. This is done by multiplying the active energy losses by the value of $C_{\text{specif. loss}}$ previously described. In Equation (9), the total wear cost $C_{\text{ttl wear}}$ is calculated. Similarly, to Equation (8), the value of $C_{\text{specif. wear}}$ is multiplied by the extended reactive energy provided in this case. In Equation (7), $C_{\text{ttl loss}}$ and $C_{\text{ttl wear}}$ are summed up to calculate the total cost $C_{\text{Q-dispatch}}$ for the operational dispatch outside the TCR.

Table 4 shows the calculated total and specific reactive power dispatch costs for the operating scenarios. It can be seen that $C_{\text{Q-dispatch}}$ differs in total for the different operating scenarios due to the various time periods considered, see Section 6. In addition, the different operating ranges result in different loss factors, as shown by the values of $C_{\text{specif.Q-dispatch}}$. $C_{\text{specif.Q-dispatch}}$ is calculated as the quotient of $C_{\text{Q-dispatch}}$ and $E_{\text{Q ttl out.TCR}}$.

7.3 | Description and Calculation of the Incentive Flat Rate F_{Grid}

The calculation of an incentive flat rate includes the value of the extended reactive power provision for a grid operator in a defined grid area. It includes all operating costs resulting from additional reactive power demand in grid operation for different operating scenarios. A well-founded calculation is recommended both from the perspective of network operation and network planning. In general, the incentive flat rate is paid in addition to the costs of the extended reactive power provision. Different approaches can be used to calculate the incentive flat rate. The following equations show three different approaches.

$$F_{\text{Grid ttl}} = C_{\text{Asset}} \cdot F_{\text{Grid specif.}} \tag{10}$$

$$F_{\text{Grid ttl OS x}} = C_{\text{Asset}} \cdot F_{\text{Grid specif. OS x}} \tag{11}$$

where

$F_{\text{specif. Grid OS x}}$: Incentive flat rate factor for operating scenario x.

$F_{\text{Grid ttl OS x}}$: Total incentive flat rate for operating scenario x.

$$F_{\text{Grid ttl}} = C_{\text{Asset}} \cdot F_{\text{Index}} \tag{12}$$

where

F_{Index}: Index factor derived from the price level for active energy.

In the first approach in Equation (10), the calculation of the total incentive flat rate ($F_{\text{Grid ttl}}$) is cost-based with a fixed factor $F_{\text{Grid specif.}}$. In this case, the amount of $F_{\text{Grid ttl}}$ results proportionally from the additional costs for the extended reactive power provision of a plant operator. $F_{\text{Grid specif.}}$ is a fixed factor and determined by the grid operator.

Another method, described in Equation (11) considers the different operating ranges of a plant. In this case, individual factors $F_{\text{Grid specif.OS x}}$ are defined for the plant's operating ranges. This enables a stronger incentive for more extreme operating scenarios, which are associated with higher expenses and costs on the plant side. Therefore, the calculation is based on both costs and operating scenarios.

In the third approach, the incentive flat rate is derived from the development of electricity prices on the wholesale market, for example, the price index of spot market products traded on EPEX Spot, as shown in Equation (12). There are various ways to calculate F_{Index}. In the decision of the Bundesnetzagentur for the reactive power market, it is suggested that the factor can be calculated from the quotient of the index prices, specifically the Phelix-DE[1] year futures for different time periods. [20]

TABLE 5 | Total and specific flat rate for Q dispatch in different operating scenarios.

Operating scenarios	Simulated days (#d)	F_{Grid} (€)	$F_{\text{specif. Grid}}$ (€ /Mvarh)
Base	3.00	58.85	0.05
Dynamic	1.54	24.72	0.05
Extreme	2.99	142.20	0.05

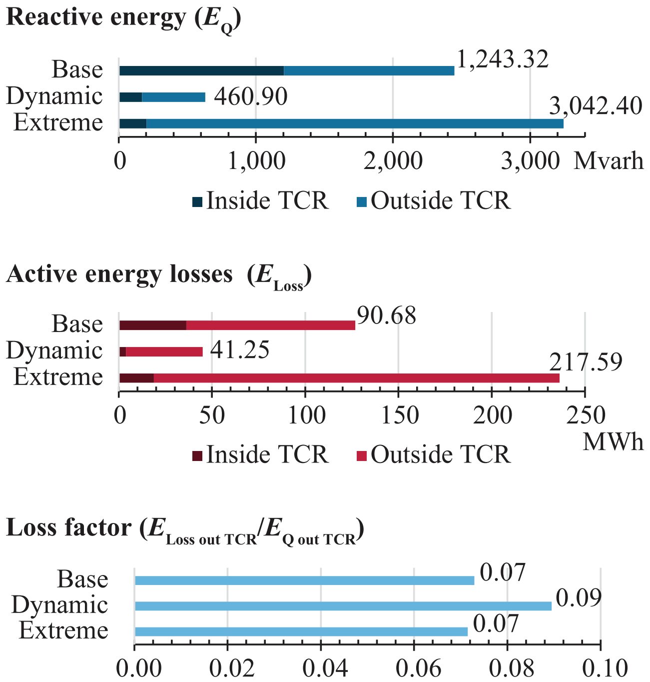

FIGURE 11 | Relevant simulation results according to operating scenarios.

For the price calculation in this study, the first cost-based calculation is chosen. This allows for simple implementation and feasibility for the time being. As described above, fixed and variable cost components on the plant side are fully considered and compensated in this approach. The incentive flat rate for this study is set at 5% of the cost of the Q-reserve and Q-dispatch, based on close consultation with the TSO 50Hertz.

$F_{\text{Grid ttl}}$ is thus calculated using $C_{\text{Q-dispatch}}$ according to Equation (10) based on the results from Table 4. The results are shown in Table 5.

The results vary due to the different operating scenarios as described before.

8 | Results

Based on the simulation model presented in Section 5 and the developed pricing model from Section 7, the results for the operational scenarios are shown in Figure 11. Only $E_{\text{Q ttl out TCR}}$ and $E_{\text{v out TCR}}$ are relevant for the calculation of the reactive power price. The figure also shows the relative reactive power-specific active energy loss $E_{\text{Loss out TCR}}/E_{\text{out TCR}}$ for the different operating scenarios.

TABLE 6 | Reactive power prices for the simulation periods of the exemplary operating scenarios.

Operating scenarios	Simulated days (#d)	$P_{\text{Q year}}$ (€)	$P_{\text{spec Q}}$ (€ /Mvarh)
Base	3.00	1,235.80	0.99
Dynamic	1.54	519.02	1.13
Extreme	2.99	2,986.11	0.98

TABLE 7 | Annual consideration of reactive power prices according to demand and planned call days.

Operating scenarios	Simulated days (#d)	P_Q (€)	$E_{Q\text{ ttl out TCR}}$ (Mvarh/a)	$E_{Loss\text{ out TCR}}$ (MWh/a)
Base	113	46,548.50	46,831.85	853.93
Dynamic	5	1,683.32	1,494.81	32.87
Extreme	5	4,994.19	5,088.34	90.98
Total	**123**	**53,226.01**	**53,415.00**	**977.78**

It can be seen that the active energy losses for the dynamic operating case are 19% higher in relation to the reactive power supplied than for the base or extreme operating scenario. This increase is also primarily due to the loss allocation (see Section 5.4), where all losses are fully allocated to the additional reactive power provision since the PV park operates mostly in STATCOM mode. Additionally, the shorter observation period of 1.54 days means that operating ranges with higher losses have a greater impact on the smaller total of data. To create an equivalent consideration to the base and extreme operating scenarios, a longer observation period should be chosen in further investigations.

Equation (13) is used to calculate the cost-based reactive power price P_Q.

$$P_Q = C_{\text{Asset}} \cdot (1 + F_{\text{Grid ttl}}) \tag{13}$$

Table 6 shows the calculated reactive power prices for the simulation periods of the individual operating scenarios The table provides the prices in Euros per Mvarh and the total prices in Euros.

The price for the reactive power supplied outside the TCR varies between 0.98 and 1.13 € per Mvarh. The price in the dynamic operating scenario is 15% higher than in the other two scenarios.

Assuming the base operating scenario occurs on 113 days per year and the other two scenarios on 5 days each, Table 7 shows the total costs for each operating scenario.

The simulation results in a total price of 53,226.00 € per year for the assumed demand days. The PV park's simulated reactive power supply of 53,415.00 Mvarh results in a total of 977.78 MWh of active energy losses outside the TCR. As mentioned at the

TABLE 8 | Comparison of operating scenario-based price and cost-weighted average price.

Operating scenarios	Simulated days (#d)	$P_{\text{Q year}}$ (€)	% Change	$P_{\text{Q year 1.04}}$ (€)
Base	113	46,548.50	+5%	48,705.12
Dynamic	5	1,683.32	−8%	1,554.60
Extreme	5	4,994.19	+5%	5,291.87
Total	**123**	**53,226.01**	**+4%**	**55,551.60**

beginning, the calculation does not include any Q-reserve costs, but these can strongly influence the price.

If a cost-weighted average price of 1.04 € per Mvarh is used instead of the operating-specific prices, the results for $P_{\text{Q year 1.04}}$ from Table 8 are obtained with the same reactive power supply and active energy losses.

It can be seen that in the observation $P_{\text{Q year 1.04}}$ in the base and extreme operating scenario, the network operator incurs on average 5% more expenses than in $P_{\text{Q year}}$. In total, the expenses for $P_{\text{Q year 1.04}}$ amount to 55,551.60 € and are thus 4% higher than for $P_{\text{Q year}}$.

In the simulation, the dynamic operating scenario has less significance due to the 5 simulated days. However, it is clear that operating ranges with higher loss factors $Q_{\text{out.TCR}}/P_{\text{out.TCR}}$ can have negative effects on the revenue of the plant operator. If operating ranges with higher losses are approached more frequently, costs for the plant operator increase, reducing both the fixed margin and the incentive. This risk can be compensated by increasing the incentive flat rate after a thorough and appropriate review. In addition, it should be noted that in the case of a one-time fixed price, market developments can also have a negative impact on the plant operator. If the price of the active energy to be purchased rises, the total cost may exceed the fixed price for reactive power. Depending on the plant operator's approach to procuring loss energy, market trends may pose an additional risk.

9 | Conclusion

In Germany, the increasing demand for reactive power and the growing share of renewable energy sources (RES) pose significant challenges to the reactive power management. At the same time, conventional power plants, which have historically provided a substantial share of reactive power, are being phased out. To ensure stable and secure grid operation in the future, new, reliable, and highly available sources of reactive power must be developed. RES have the potential to play a key role in this transition, as they are generally connected to the grid via highly controllable inverters. However, their technical potential has largely remained untapped due to the lack of economic incentives for fully utilizing these capabilities.

To address this issue and in alignment with the EU Directive 2019/944 [21], which mandates a market-based, transparent, and non-discriminatory procurement of reactive power, Germany has introduced a reactive power market, set to commence in early to mid-2025. In the future, RES operators will be able to participate in tenders issued by grid operators to provide reactive power beyond the mandated requirements like in the Technical Connection Rules. However, uncertainties persist, not only regarding the novel reactive power market, its cost structures, and price developments but also due to concerns that increased reactive power provision could negatively impact the lifespan of RES components.

Against this background, this study specifically addresses key aspects outlined in the introduction: (1) the technical feasibility and regulatory challenges of reactive power provision from RES, (2) the impact of increased reactive power provision on inverter wear and tear, and (3) the economic implications of extended reactive power operation. Through detailed simulations and practical application to a real 350 MW PV park on the extra high voltage (EHV) level, this study provides valuable insights into the implementation of reactive power provision from RES. The close collaboration with the transmission system operator (TSO) 50Hertz, the PV park developer, and the inverter manufacturer Delta Electronics ensures that the results are highly relevant for real-world applications.

The study examined various factors that influence inverter lifespan. Capacitor aging and external degradation factors, such as cosmic radiation, were found to have negligible effects on inverter lifetime, reinforcing the conclusion that thermal cycling in power semiconductors is the dominant aging mechanism. Other degradation mechanisms, such as relay wear or passive component drift, were not explicitly considered in the pricing model, as their impact was deemed marginal. However, future research could further refine cost estimations by incorporating these aspects.

Overall, the study confirms that increased reactive power provision negatively impacts inverter lifespan. The extent of this impact ranges from a 10.4% reduction when QbyNight is activated only on weekends to a 38.4% reduction when QbyNight is active throughout the entire year. The study further demonstrates that the overall frequency of reactive power provision has a greater effect on inverter lifetime than the absolute magnitude of reactive power supplied. This suggests that primary aging effects occur at lower reactive power levels, while additional wear effects at higher levels diminish. From a financial perspective, the study quantifies semiconductor wear costs with an average price of 0.34 € /Mvarh across all scenarios. These findings indicate that higher reactive power provision does not proportionally increase wear-related costs, making targeted market incentives for increased reactive power provision economically viable.

Together with the TSO, specific operating scenarios have been identified for the analyzed PV park in which reactive power is to be provided in the future. These scenarios are primarily characterized by the loss of reactive power potential due to the unavailability of conventional power plants. For these scenarios, future reactive power demands were estimated, and associated losses for different operating conditions were analyzed. In order to compensate for the increased provision of reactive power, the cost components influencing pricing were identified, forming the basis for the pricing model developed in this study.

The proposed pricing model quantifies reactive power dispatch costs based on multiple cost components, primarily active energy losses and semiconductor wear. The analysis highlights that the energy loss factor (MWh/Mvar) is the most critical parameter affecting pricing, as it strongly depends on plant-specific characteristics and operational strategies. The results also show that the losses and minimal wear effects caused by reactive power provision outside the TCR can be incorporated into a market-based procurement framework, ensuring fair compensation for plant operators while enabling a cost-efficient, flexible, and dynamic reactive power source.

A key takeaway from this study is that the economic viability of reactive power provision is highly sensitive to the plant operator's strategy for procuring active energy to compensate for increased losses. Market developments influencing electricity prices could significantly impact reactive power pricing and long-term profitability, underscoring the importance of incorporating reserve pricing mechanisms into future procurement strategies. While reserve costs were not explicitly included in this study due to limited empirical data, they are expected to play a crucial role in final price determination.

Future research should focus on real-world validation through laboratory or field testing, enabling a more precise assessment of operational risks and additional costs from both grid and plant operator perspectives. Such studies are already planned as part of the Q-REAL research project [34], involving both 50Hertz and the PV park operator.

Ultimately, establishing a transparent and well-structured pricing framework for reactive power provision is essential to achieving a balanced cost-benefit ratio for both system and grid operators. The operating scenarios considered in this study provide an initial reference, but a broader dataset or standardized methodologies could improve the reliability of future pricing models. Further research should aim to quantify additional risks and stakeholder concerns, optimizing the integration of inverter-based reactive power sources into the high-voltage and extra-high-voltage grid.

Author Contributions

Analysis of hardware effects of extended reactive power provision and loss analysis of inverters: S. Eichner and R. Grab. Analysis of loss components, modeling and conceptualization of simulation series, and evaluation of simulations: H. Köppe. Analysis of reactive power demands and conceptualization of operating scenarios: H. Köppe, F. Sass and M. Schuster. Analysis of pricing components, development of the pricing model, evaluation, and economic analysis: M. Schuster. Project administration and supervision: B. Engel. All authors have read and agreed to the published version of the manuscript.

Acknowledgements

This study was conducted in collaboration with 50Hertz Transmission GmbH, Delta Electronics, a planning and operating company for PV parks, and two research institutions: the elenia Institute for High Voltage Technology and Power Systems, and the Fraunhofer Institute for Solar Energy Systems ISE.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper. Although the study was originally commissioned by 50Hertz Transmission GmbH, there was no influence on the research process or outcomes. The research was conducted independently and objectively.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request. However, access to certain data may be restricted due to confidentiality agreements and proprietary information from industry partners. Requests will be evaluated on a case-by-case basis in accordance with company policies and data-sharing agreements.

Endnotes

[1] The Phelix-DE year future is a financial contract representing the average electricity price for delivery in Germany over the course of a year, traded on the EEX (European Energy Exchange).

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