DATA-DRIVEN DETERMINATION OF FCA

DATA-DRIVEN DETERMINATION OF FLEXIBLE CONNECTION AGREEMENTS (FCA)

Towards quantitative, evidence-based grid flexibility management

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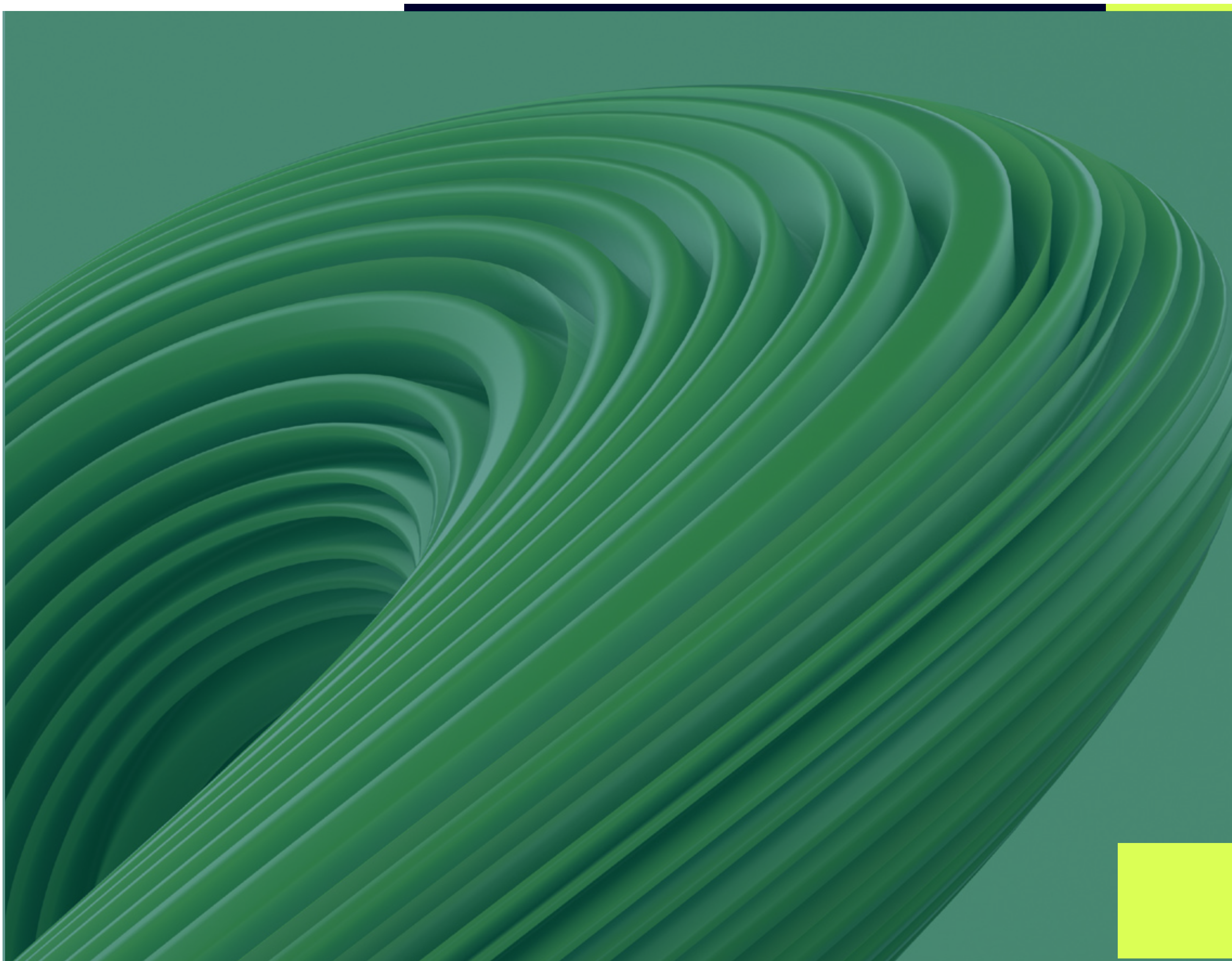
München, 09.02.2026

Disclaimer

The methodology presented for determining FCA limits is currently in a beta stage. P3 Energy Solutions has developed an analytical tool to automatically calculate and evaluate FCAs focusing on transformer loading which is only one of multiple technical limits to assess within the grid connection check. All data shown in this whitepaper is exemplary, derived from historical grid loading patterns in collaboration with Bayernwerk Netz GmbH. The primary objective of this paper is to introduce a transparent, data-driven methodology for determining FCA parameters for feed-in and demand assets. The case studies included serve as illustrative and fictitious examples of the approach rather than definitive results.



1. Key Findings

Purpose and Context

This whitepaper presents a quantitative, data-driven methodology for determining Flexible Connection Agreements (FCAs) at asset level, developed in collaboration with Bayernwerk Netz GmbH. FCAs are a key instrument to accelerate grid connections under defined curtailment conditions, addressing the fast-growing volume of connection requests and the resulting imbalance between connection demand and available grid capacity. Unlike previous approaches focused on project developer interests, this methodology prioritizes grid operator requirements for transparency and operational security.

Core Capabilities

The methodology calculates FCA limits for both feed-in and demand assets using exemplary loading data and percentile-based logic. It accounts for seasonal variability, applies step function logic for practical implementation, and ensures compliance with the N-1 criterion for demand requests. A unique feature is its ability to combine feed-in and demand FCA calculations, enabling strategies for hybrid assets such as battery energy storage systems (BESS).

Benefits

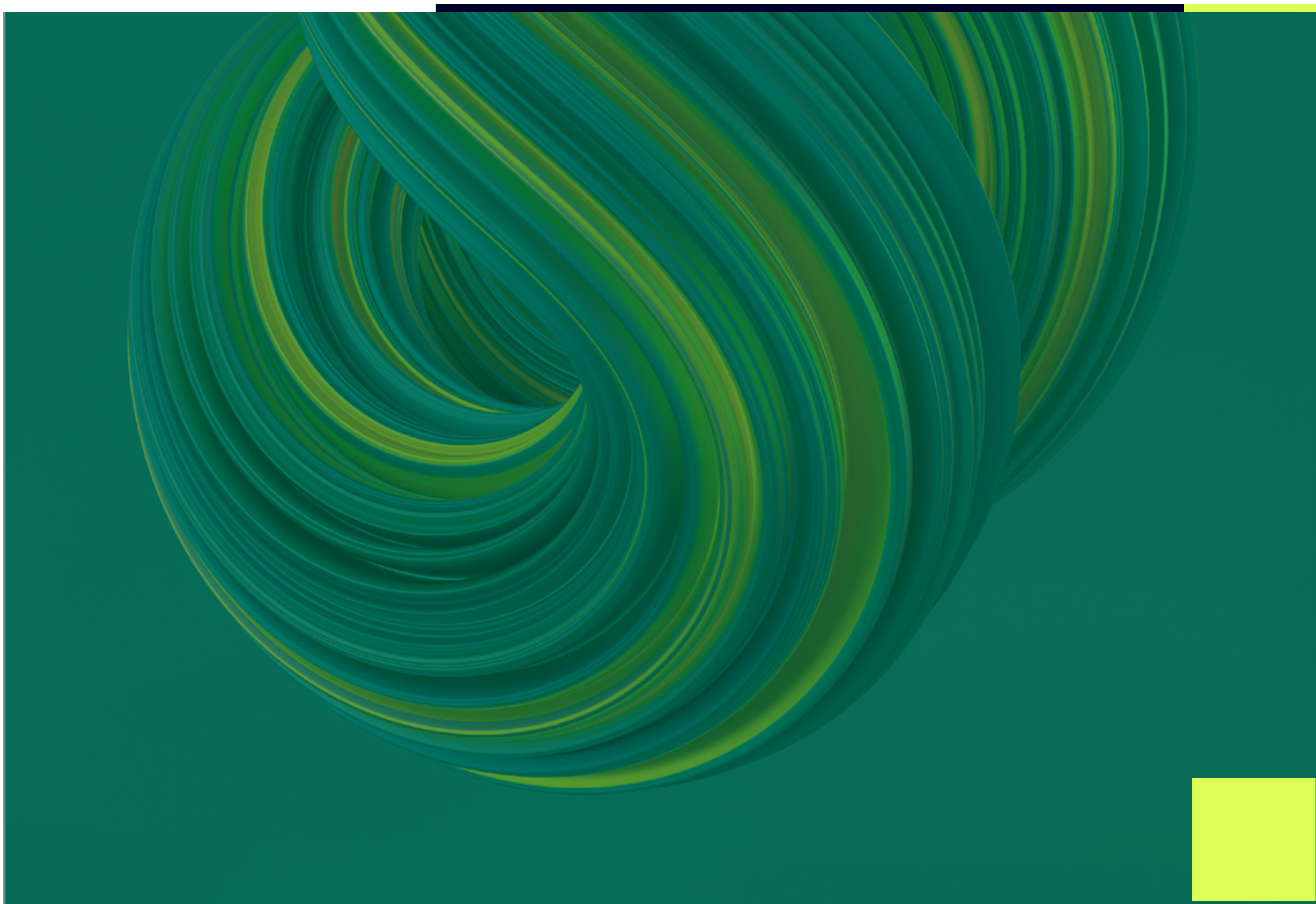
FCA-based connections enable earlier project realization without immediate reinforcement and improve grid utilization compared to static capacity limits or conventional static control. Adjustable percentile parameters and step-function configurations allow an explicit differentiation between customer-side curtailment impacts and grid-operator-side redispatch measures, thereby balancing operational responsibility and risk allocation.

Evaluation Takeaways

Case studies show FCA-based connections can unlock substantial capacity: up to 29 % more energy for feed-in assets and 65 % more for demand assets compared to the conventional static, worst-case connection assessment (fixed connection capacity derived from extreme-case power-flow studies), while maintaining operational limits. Sensitivity analysis highlights how percentile selection influences curtailment and redispatch, enabling operators to optimize based on system priorities.

Future Work

Further development will refine synthetic demand and flexibility profiles for improved customer-side evaluation, extend combined FCA strategies for hybrid assets, and introduce automated optimization of percentile and buffer parameters. These enhancements will strengthen the methodology as a robust planning and operational tool for DSOs.



2. Introduction

The transformation of the energy system in Germany and across Europe continues to accelerate. The rapid expansion of renewable generation, driven by national and European climate targets and economic advantages, has led to a steep increase in connection requests for new plants and flexible assets. German network operators currently face grid connection applications of standalone BESS exceeding 500 gigawatts, far surpassing available network capacity. This imbalance between demand for connections and physical grid connection capability has made transparent and efficient allocation mechanisms essential.

In response, recent amendments to the Renewable Energy Act (§ 8a EEG 2023) and the Energy Industry Act (§ 17 Abs. 1–2b EnWG) introduced new instruments for conditional grid access. Flexible Connection Agreements (FCAs) allow network operators to grant connections under defined curtailment or availability conditions, enabling the use of currently unused grid potential and earlier project realization without immediate grid reinforcement. These instruments mark a fundamental shift from the principle of firm access toward a more time-resolved, operational-state-based coordination of grid use, leveraging time series assessments rather than static worst-case assumptions.

The discussion surrounding FCAs has intensified in recent months, particularly due to the surge in stationary battery energy storage systems (BESS). Grid operators, project developers, and associations have initiated conceptual debates on possible contract structures, implementation processes, and technical prerequisites. However, despite this growing interest, there remains a lack of transparency and methodological clarity. Most current discussions address regulatory feasibility and contractual principles but do not provide reproducible calculation methods to determine the quantitative limits of FCAs at asset level. Importantly, FCAs are not limited to storage. They apply equally to feed-in and demand assets and therefore form a cross-sectoral element of modern network management.

This whitepaper builds on the regulatory and analytical groundwork of ongoing studies and collaborations, focusing on the practical question that remains unanswered: **How can grid operators determine FCA limits in a transparent, data-driven, and reproducible manner based on real loading of the connection point?**

By combining operational grid data from Bayernwerk Netz with a structured analytical framework, P3 Energy Solutions developed and tested a quantitative methodology for FCA determination at transformer level, which is presented in this report. The resulting stepwise access functions provide connection parties with a transparent, contractually defined capacity profile, enabling robust business-case calculations compared with "curtailment hours" based approaches. The results aim to contribute to the ongoing national discussion on FCA design, providing a replicable approach for both distribution system operators and market participants.

2.1. Status Quo review

Flexible Connection Agreements are increasingly recognized as an effective instrument to unlock underutilized, already built and paid-for grid infrastructure, thereby accelerating new grid connections and optimizing the utilization of existing assets. They enable new assets to connect under defined curtailment conditions rather than waiting for conventional grid reinforcement. While the EU Electricity Market Design Directive (Art. 6a EMB-RL) has been implemented in several member states, no publication to date has presented a transparent, data-driven methodology for determining FCA limits at the level of individual grid assets.

The research institute FfE addressed flexibility and grid operation in its study *"Netzverträglicher Ausbau von Batteriespeichern"* (2024). The analysis demonstrated that coordinated operation of storage systems could reduce redispatch volumes by up to 30 %, emphasizing the importance of data transparency and standardized interfaces. However, the study did not define how grid connection limits or safety buffers should be quantified for individual assets, leaving the concrete determination of FCA parameters unresolved.

At the European level, reports by the Council of European Energy Regulators (CEER, 2023) and Boston Consulting Group's *"Mind the Queue"* (2025) highlight international experiences with non-firm or flexible connection models. Both underline that flexible access can significantly reduce connection delays, yet national frameworks differ widely and lack harmonized methods for defining curtailment levels or availability tiers.

In Germany, initial steps toward implementation have begun. N-ERGIE Netz GmbH announced the introduction of *Flexible Netzanschlussvereinbarungen* in 2025, allowing new PV, wind, and storage projects to connect in constrained areas under temporary curtailment. However, no public information is available on how permissible capacities or curtailment rules are determined. Other DSOs, such as EWE Netz, have indicated similar intentions but likewise have not published technical criteria.

Overall, the reviewed literature and early initiatives confirm regulatory readiness for FCAs but reveal a consistent gap: no grid operator or study has yet defined a reproducible, data-driven methodology for determining FCA limits and safety buffers based on empirical transformer loading. This methodological step forms the core of the present work.

3. Design framework

The analysis is based on exemplary multi-year loading data of substations or individual transformers connecting the high-voltage to the medium-voltage grid. In addition, information on already approved grid connection requests for both demand and feed-in is included, enabling an assessment of the relationship between existing network utilization and additional confirmed connection requests. While this study uses exemplary substation loading data, the methodology can be applied to any loading dataset, provided the format and resolution are appropriate.

Figure 1 illustrates an exemplary dataset of grid loading, where positive values represent power flow from the high-voltage to the medium-voltage grid (corresponding to demand), and negative values indicate reverse power flow caused by feed-in exceeding local demand. This bidirectional behavior is critical for FCA determination, as both high-demand and high-feed-in periods define the limiting cases for grid flexibility.

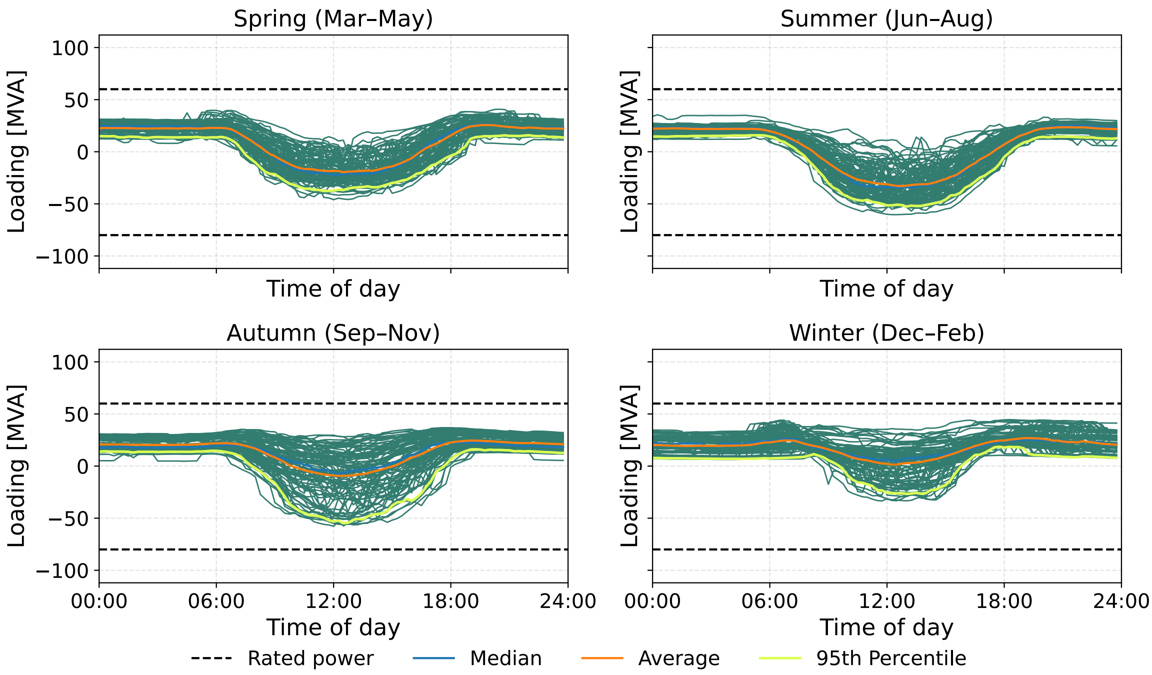


Figure 1: Daily loadings of an exemplary substation split across four seasons in a given year.

The seasonal variation shown in Figure 1 highlights the influence of distributed photovoltaic generation on network behavior. Negative loadings increase significantly during spring and summer. These observations indicate that FCA determination must account for seasonal variability, as available grid capacity changes throughout the year.

To incorporate approved connection requests and evaluate the impact of generation and load patterns on FCA determination, synthetic profiles of major generation technologies and load patterns are used.

For generation, representative time series for photovoltaic, wind, and biogas plants were provided by Bayernwerk Netz, while standardized consumption profiles from the German Association of Energy and Water Industries (BDEW) could be applied for demand customers (load). However, as a conservative measure, a constant load on demand requests was assumed to account for the possible continuous operation at 1.0 p.u. contracted.

To capture the variability of renewable generation and ensure robust FCA determination, generation profiles are synthesized to reflect maximum monthly generation. Figure 2 shows daily wind profiles per month in blue, with the maximum profile indicated by a dotted line, which is used for FCA calculation. The same approach was applied to PV and biogas profiles.

4. FCA Methodology

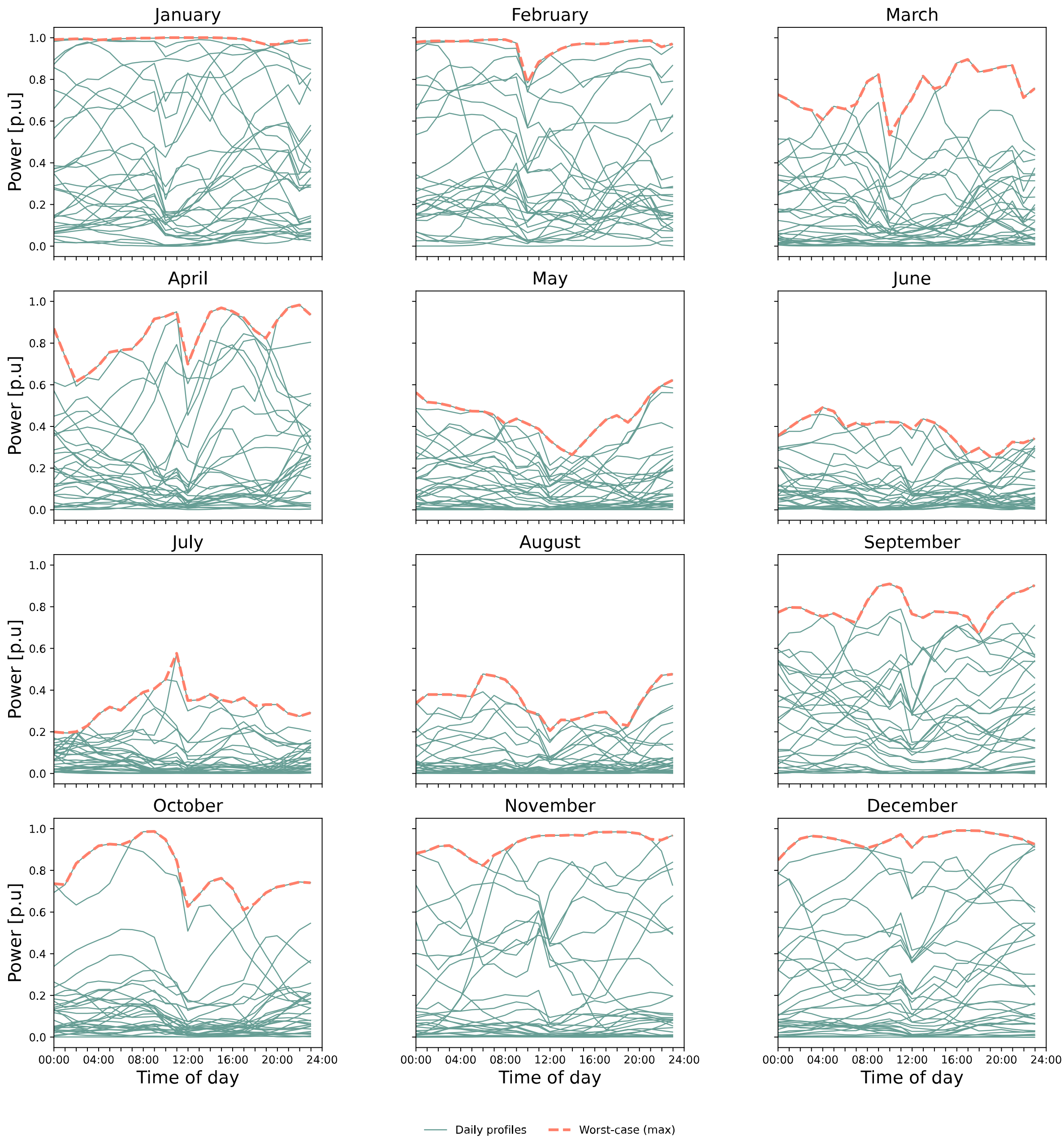


Figure 2: Daily synthetic wind profile over a year, split across 12 months. The maximum curve per month applied for the FCA calculation is shown as a dotted line.

The developed methodology distinguishes between feed-in and demand FCAs. This separation is necessary for two reasons:

1. **Operational behavior**: Feed-in assets exhibit weather-driven volatility, while demand patterns are typically more stable and predictable.
2. **Available curative measures:** Feed-in can be managed through redispatch mechanisms, whereas demand cannot be curtailed by the grid operator. These operational realities require separate analytical treatment.

Since asset loading varies significantly by location and season, the methodology determines individual FCA limits per asset or asset cluster. To account for temporal variability, an aggregation parameter defines how historical data is grouped for analysis. Depending on this parameter, FCA limits can be calculated for an entire year, individual quarters, months, or seasonal periods. In this study, the aggregation parameter is set to four seasons:

- Winter (December–February)
- Spring (March–May)
- Summer (June–August)
- Autumn (September–November)

Time series analysis in the highly meshed high-voltage network was not part of this study. Considering the total grid loading allows for a simplified approach to account for the loading in the high-voltage network.

The **total grid loading**, which must not be exceeded by any demand connection request. Including this constraint requires loading data from the high-voltage grid, which in this paper is synthesized by aggregating and scaling substation characteristics. The methodology is generic and not tied to specific connection requests. Whether FCA limits are calculated per request or as available capacity to be allocated later depends on the grid operator's FCA strategy.

4.1. Feed-in FCA

For feed-in assets, daily loading at the connection point fluctuates due to photovoltaic and wind generation. To derive a representative loading profile for FCA determination, a percentile-based approach is introduced. Statistical averages or medians would fail to capture extreme loading events relevant for grid security. Therefore, a **percentile parameter** is applied to represent loading at each time step, allowing adjustment of how restrictive the FCA should be. Setting this parameter to 95 results in a profile that covers 95% of all loading values per time-of-day timestep within each aggregation period.

Figure 3 illustrates exemplary loadings of an already heavily loaded transformer with additional 6 MW approved connection requests (feed-in commitment). The green line displaying the calculated 95th percentile of loading. Blue areas represent the bandwidth of measured daily loadings for the respective aggregation, while the orange area includes the feed-in commitment using the synthetic profiles described in the design framework. The blue area overlaps differently with the red area for the seasons, reflecting the varying bandwidth of loading. Around midday, loading reaches its maximum and can already exceed the rated power, affirming the need for flexible connection agreements. For the FCA determination, the power of the transformers was limited to 100% of the nominal power rating for new requests.

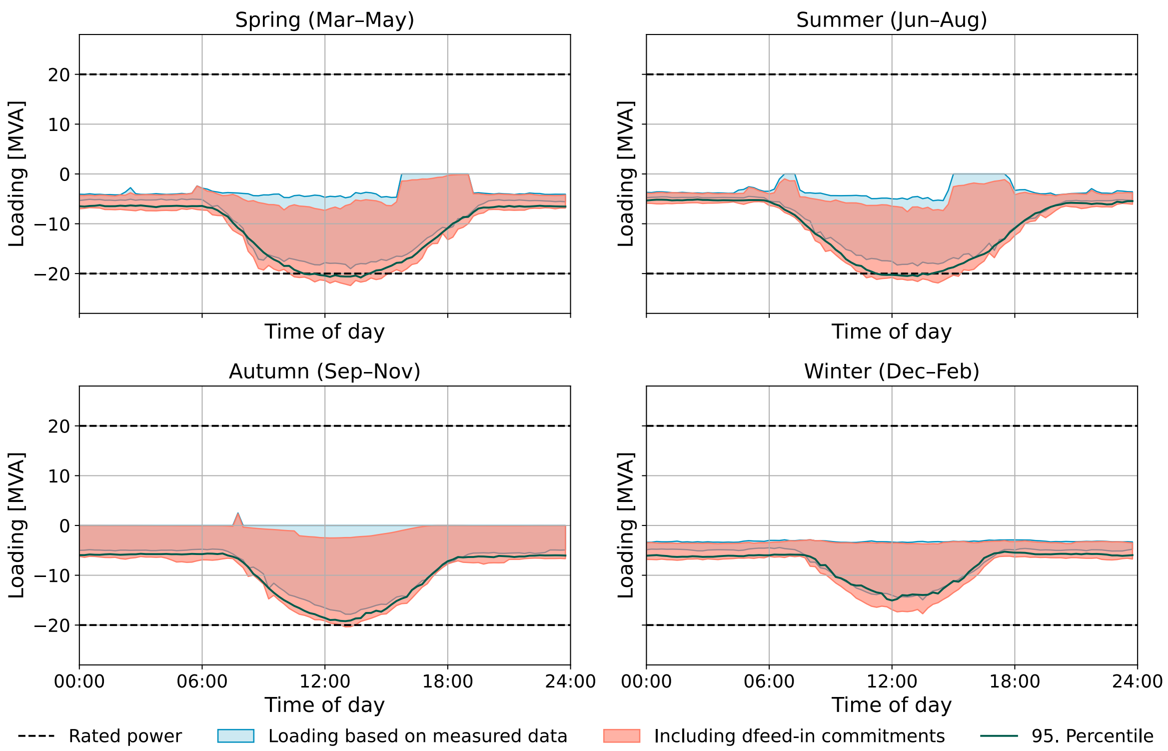


Figure 3: Loading of an exemplary transformer including the calculated loading from contracted grid connections (feed-in commitments).

In practical terms, the remaining capacity below the 95th percentile curve represents the power available for additional grid connections under an FCA. This available capacity is converted into a stepwise "stair" function, following approaches used in previous pilot projects. The stair function simplifies interpretation and application and can be adjusted through three parameters:

Step logic: Determines whether the step value represents an average (midpoint) or restrictive (endpoint) condition.

Step length: Defines temporal resolution (e.g., 15-minute or hourly intervals)

Minimum step height: Ensures small steps are avoided by introducing a threshold for changes.

These parameters allow the FCA curve to be tailored to either more restrictive or more permissive conditions, depending on operational flexibility and compensation measures. Feed-in commitments were not considered in the following evaluation resulting in FCA restrictions as shown in Figure 4.

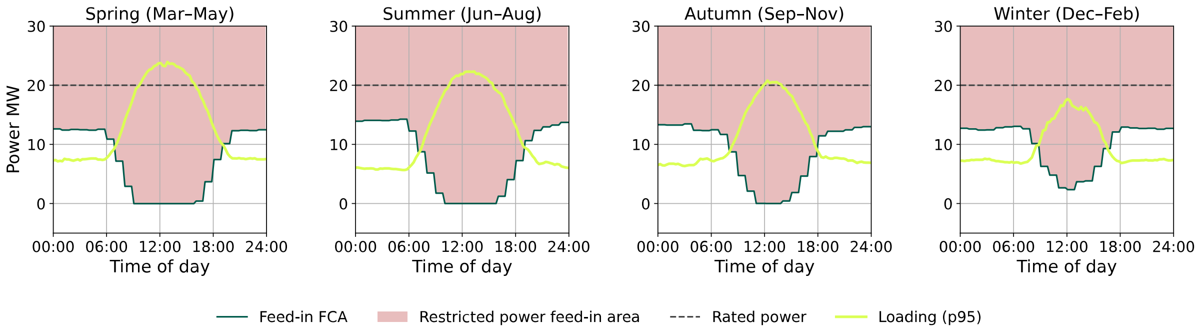


Figure 4: Feed-in FCA for the exemplary substation, split across four seasons.

4.1.1. Evaluation of the feed-in FCA

The impact of the FCA must be assessed from both perspectives: the grid operator and the asset owner. For this evaluation, two hypothetical connection requests are considered: A 5 MW photovoltaic (PV) plant, and a 5 MW wind power plant.

First, the FCA is applied to the synthetic profile of each asset to determine the number of affected hours and the magnitude of curtailed energy. While FCA determination assumed maximum monthly generation profiles for PV and wind, the evaluation uses standard synthetic profiles to provide an accurate representation of full-load hours.

Figure 5 illustrates the effect of the FCA on PV and wind profiles. Since the transformer was previously loaded with PV generation, the FCA has a stronger impact on the PV profile, curtailing approximately 833 MWh over the year and affecting roughly 700 hours. In contrast, the wind profile experiences significantly less impact, with about 150 MWh curtailed during 126 hours.

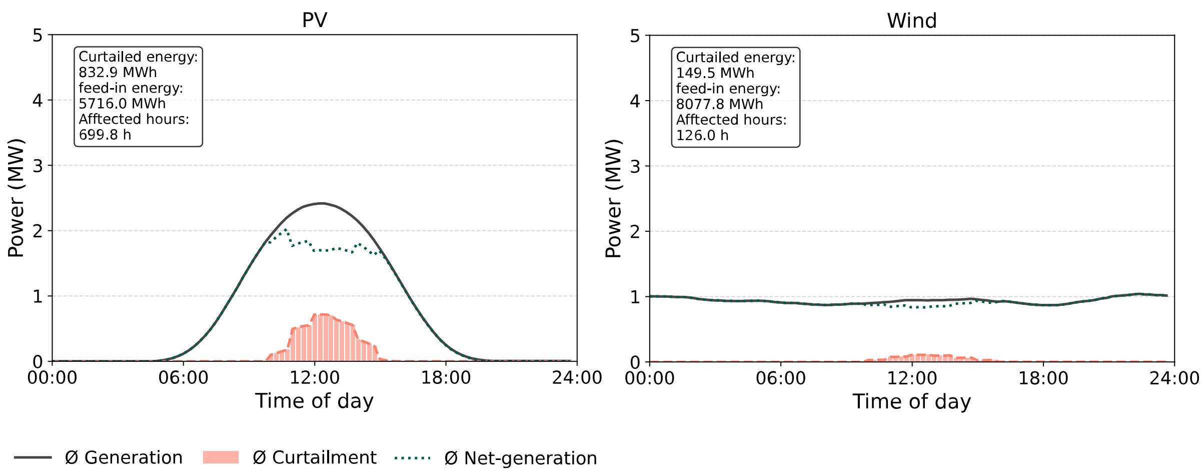


Figure 5: Impact of FCA on generation profile of PV (left) and wind (right).

In a second step, the magnitude of feed-in energy for both asset types is compared across four grid connection setups:

1. **No restriction:** Represents maximum feed-in energy based on the synthetic profile.
2. **Static capacity limit**: Based on the difference between maximum observed loading and rated transformer capacity. For the exemplary transformer, this results in a remaining capacity of 1.66 MW (20 MW – 18.34 MW). The rated power of the generation unit is scaled down accordingly.
3. **Static control (PAV,e)**: Implements a controller in accordance with VDE AR-N 4110, limiting feed-in to 1.66 MW while the asset retains a theoretical maximum of 5 MW.
4. **FCA-based connection**: Applies the FCA curve derived in the previous section.

Figures 6 and 7 present the comparison of feed-in energy across these four setups for PV and wind respectively. For PV, the FCA enables 5,716 MWh of feed-in—29 % more than the static control approach and only 13 % less than unrestricted operation. For wind,

FCA-based connection delivers 20 % more energy compared to PAV,e and 2 % less than unrestricted operation.

These results demonstrate that accurate FCA determination can unlock significant value for both asset owners and grid operators by increasing grid utilization without compromising operational security.

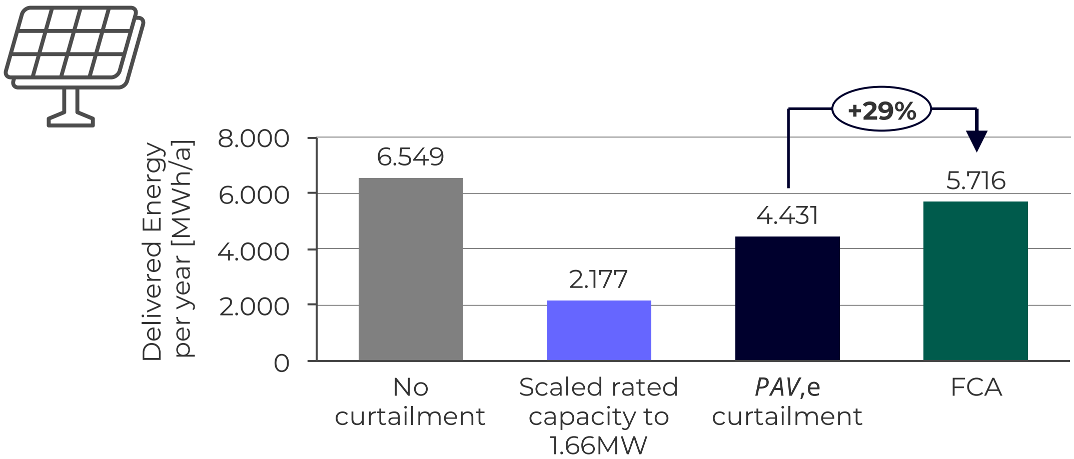


Figure 6: Comparison of feed-in energy from PV across different grid connection methods.

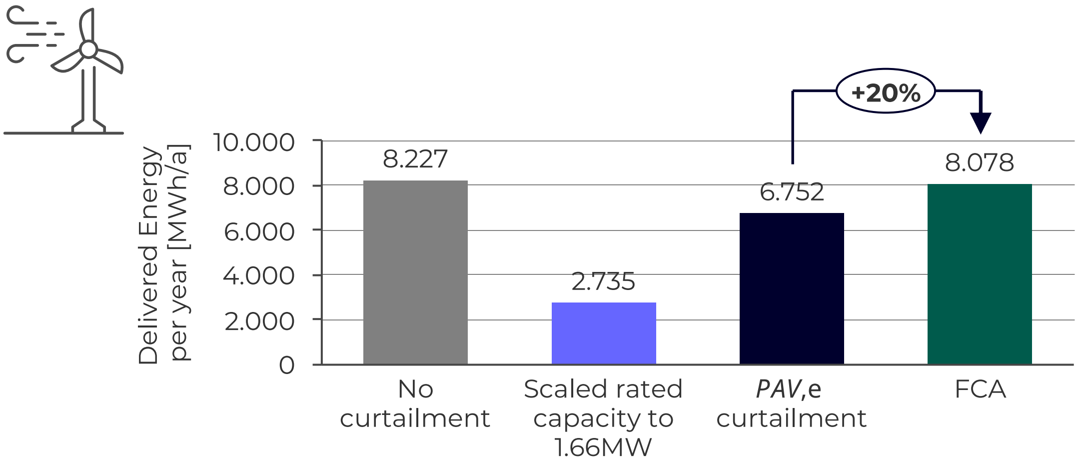


Figure 7: Comparison of feed-in energy from wind across different grid connection methods.

Finally, the impact of the FCA on transformer loading is analyzed. Figure 8 shows the additional loading from the 5 MW PV plant without FCA, resulting in overloads during spring and summer. Figure 9 illustrates the same scenario with the FCA applied, reducing overloads to within feasible operating limits. This validates the methodology. We do see minor overloading at around 14:00 in spring, summer, and autumn due to the percentile chosen for the FCA determination, which is acceptable, as the grid operator can mitigate these events using redispatch.

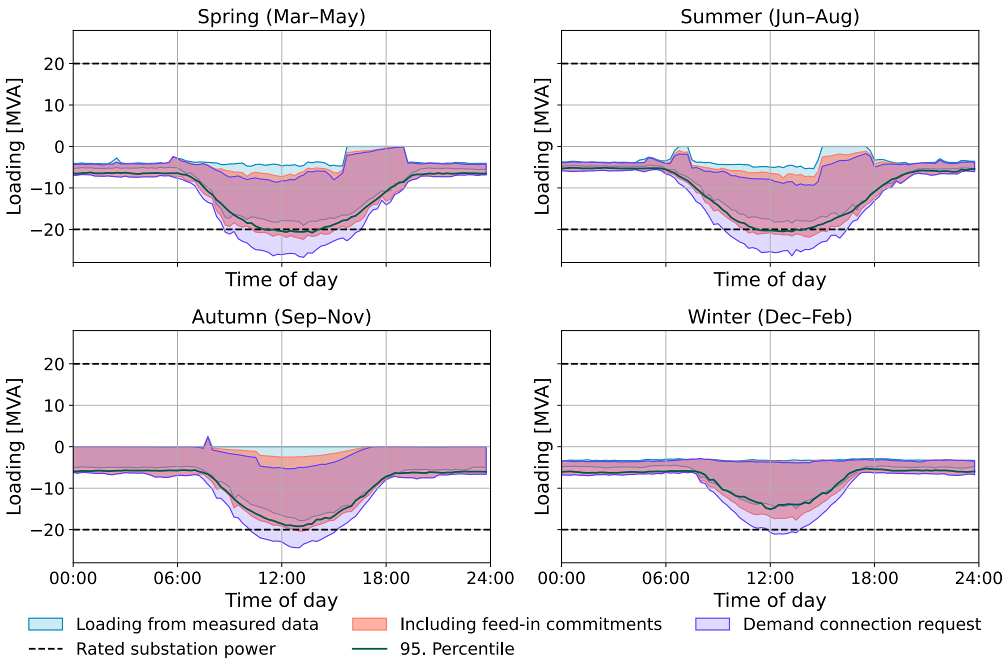


Figure 8: Loading of the transformer with the added 5MW PV plant without curtailment.

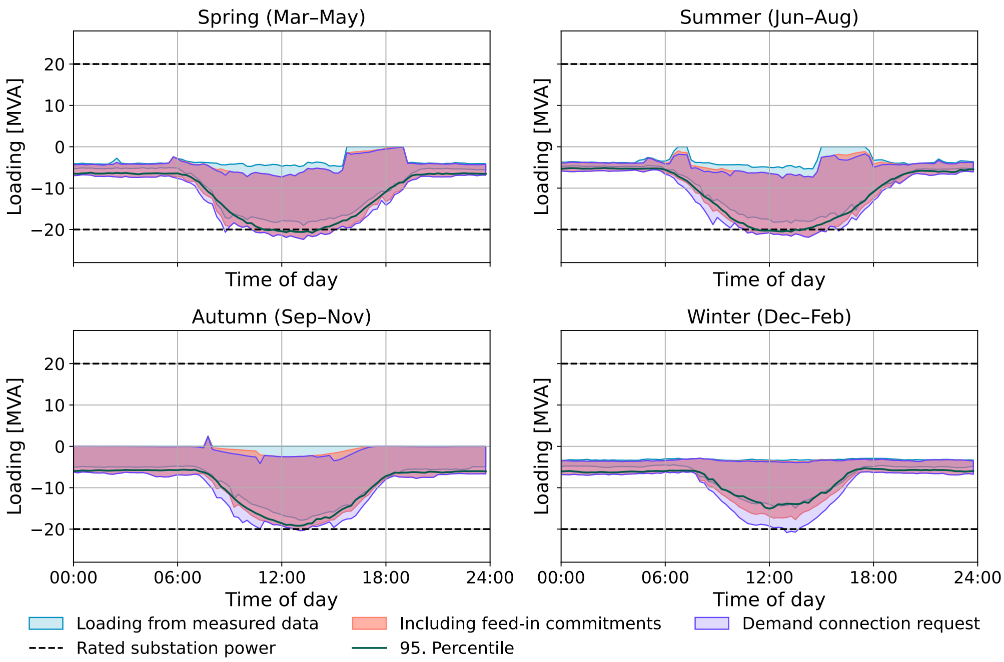


Figure 9: Loading of the transformer with the added 5MW PV plant and FCA applied.

4.1.2. Redispatch

In a subsequent step, the impact of the connection request with FCA on additional redispatch measures is evaluated as a key performance indicator (KPI) from the grid operator's perspective.

Redispatch energy is defined as the time integral of the asset loading exceeding a specified power threshold. For the evaluation, the synthetic generation profile of the connection request, with the FCA limitations applied, is superimposed on the existing asset loading. All timesteps in which the resulting power exceeds the predefined threshold are counted as redispatch-relevant operation.

Figure 10 illustrates the expected redispatch for the exemplary asset with a maximum admissible loading of 1 p.u. The red area denotes the additional redispatch caused by the new connection operating under FCA.

In principle, the methodology allows the annual redispatch energy attributable to a plant connected under an FCA to be reduced to zero, if the FCA limits are derived from the asset's maximum historical loading. However, to enable a practical trade-off between additional generation and redispatch effort, the 95th percentile of the loading is used for the FCA limits as described in chapter 4.1. This results in a limited number of additional hours in which the power exceeds the threshold and is therefore handled via redispatch. Furthermore, increasing the permissible loading threshold for a limited duration (short-term overload capability) can reduce the required redispatch energy with manageable, or in some cases negligible, impact on transformer ageing and thermal stress, provided that the corresponding equipment ratings and operational guidelines are respected.

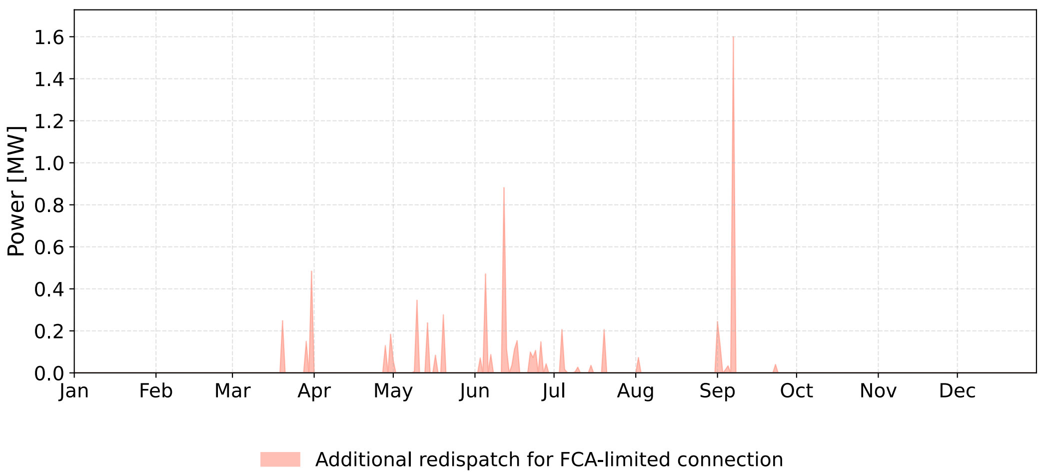


Figure 10: Redispatch energy required at the exemplary transformer with the additional asset under FCA

4.1.3. Sensitivity Analysis

In a last evaluation step, a sensitivity analysis across the percentile used for FCA determination is conducted, comparing the curtailed feed-in energy and required redispatch energy. This analysis can then be used to determine an optimal and individual percentile of loading for the FCA calculation per transformer or substation. Figure 11 shows the results of the sensitivity analysis for the range of the 70th to the 100th percentile. Naturally, the strictness of the FCA increases as the loading percentile used for determination increases. The curtailed feed-in energy increases linearly until p90, then exponentially increases until p100, as now the last loading spikes of the transformer are included and the FCA significantly limits feed-in during noon hours. On the contrary, the expected additional redispatch energy required when connecting the asset decreases nearly linearly between the 70th and 100th percentile. Since this exemplary transformer had already been subject to redispatch measures prior to the new grid connection request, redispatch energy is still needed at very high percentiles. Other transformers show no additional redispatch at percentiles between p90 and p95. This range could then be taken as an optimal percentile range for feed-in FCA determination. However, since loading profiles are individual, the optimal percentile per asset can differ.

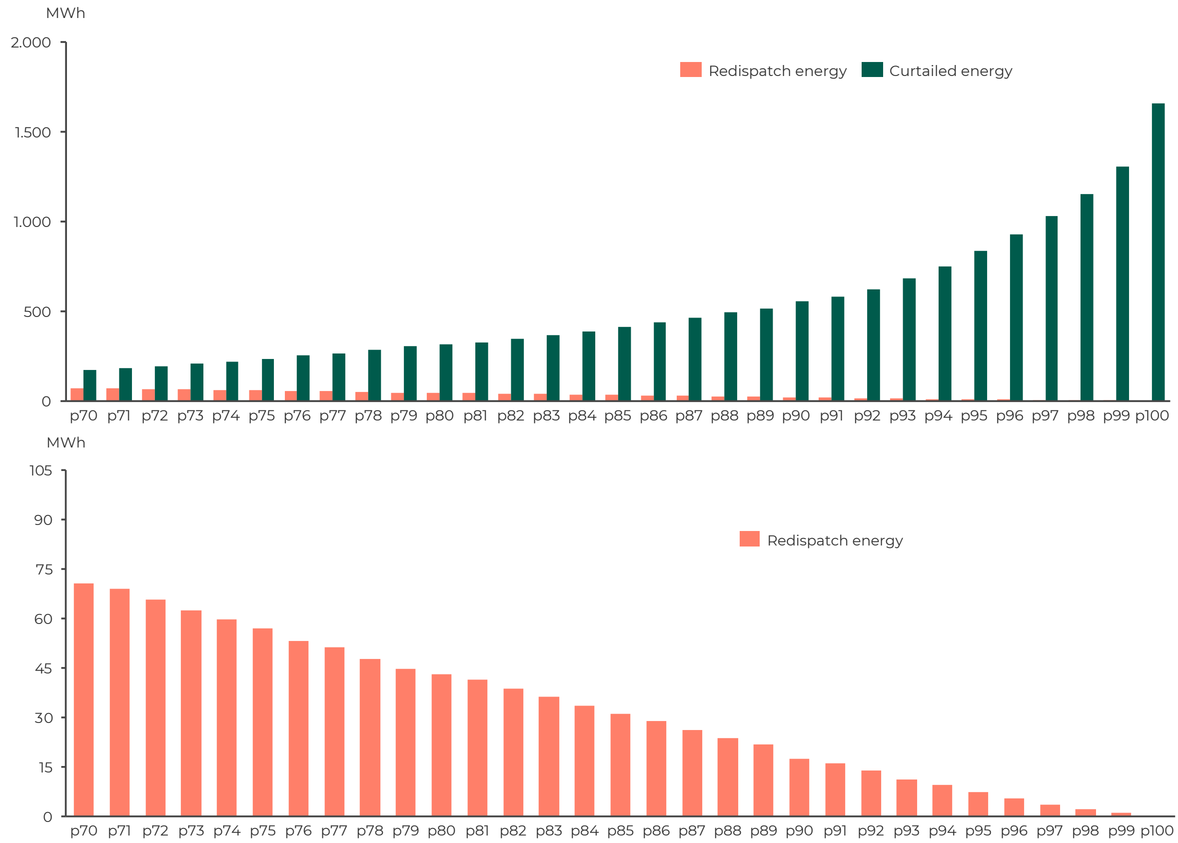


Figure 11: Sensitivity analysis of the loading percentile (p) using the curtailed feed-in energy and redispatch energy.

4.2. Demand FCA

Unlike feed-in FCA, where curtailment can be managed through redispatch, demand FCA requires a more conservative approach because the grid operator cannot curatively control excessive consumption. Therefore, the methodology assumes a worst-case scenario: the **100th percentile** (maximum) loading is taken for each 15-minute timestep across all historical data years. This ensures that the FCA reflects the highest possible loading conditions that could occur.

To further enhance operational security, an additional **safety buffer parameter** can be applied. This parameter increases the assumed loading by a configurable margin, making the FCA stricter if required. Figure 12 illustrates the loading of an exemplary, moderately loaded substation, with the maximum line indicating the worst-case loading described above.

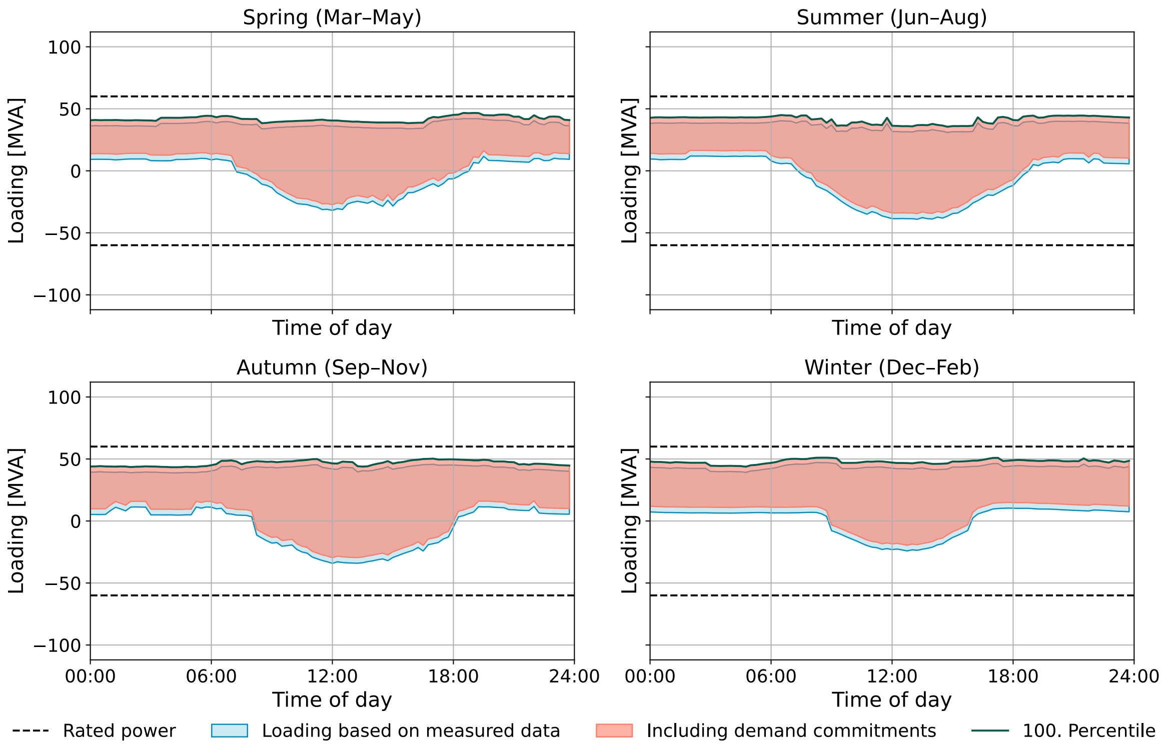


Figure 12: Loading of an 80MW substation across the four seasons including loading data from historical measurements and additional demand from granted grid connection assets (loads/storage)

The step-function logic applied to the demand FCA follows the restrictive approach outlined for feed-in FCA. In contrast to feed-in FCA, the strongest restrictions occur during morning and evening hours, when industrial and household consumption typically peaks.

4.2.1. N-1 criterion

When supplying demand, the N-1 security criterion must be considered by the grid operator. In this methodology, N-1 security is incorporated in a straightforward manner to maintain broad applicability. The remaining capacity under an N-1 contingency is approximated by subtracting the rated power of the largest transformer from the sum of all transformers connected to the substation. This represents the maximum substation capacity assuming the outage of the largest unit.

This approach requires only minimal input data—transformer ratings and their allocation to substations—and avoids the complexity of full load-flow analysis. For additional refinement, feed-in only or auxiliary transformers are excluded from N-1 consideration if possible to identify by labels or power ratings.

For FCA calculation, the substation loading time series is evaluated against the reduced N-1 capacity. For each 15-minute timestep, the available power margin under N-1 is obtained by subtracting observed loading from the N-1 capacity. This time-dependent margin is then converted into the FCA step function using the same procedure as in the non-N-1 case, resulting in FCA limits explicitly compliant with the simplified N-1 criterion.

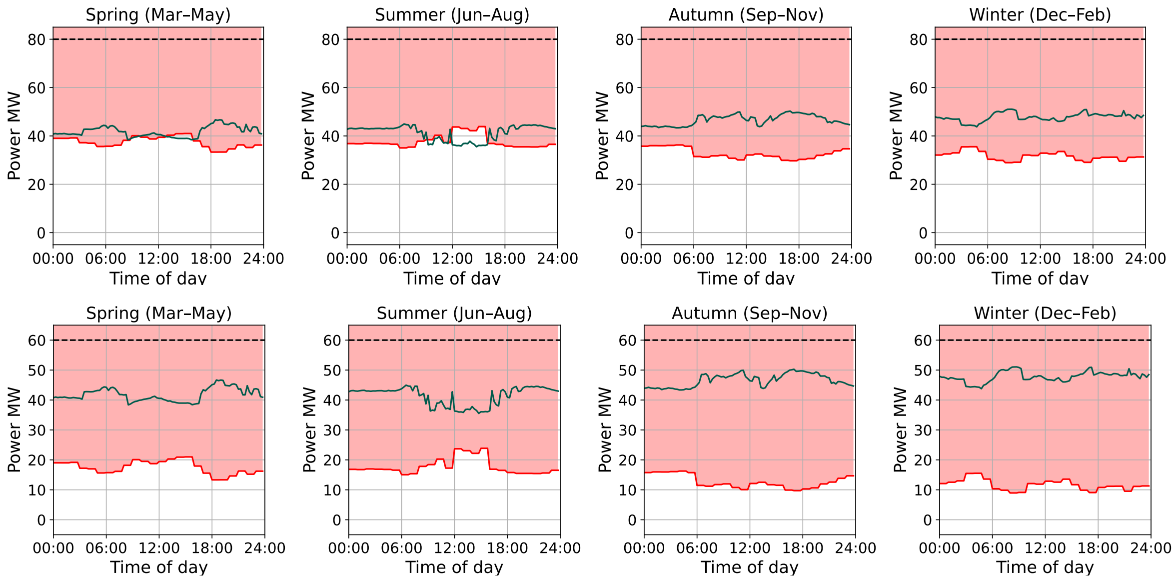


Figure 13: Demand FCA without N-1 criterion (top) and with N-1 criterion (bottom) for an exemplary substation

4.2.2. Total grid loading

In addition to local asset constraints, the methodology provides the option to consider a system-level constraint based on the total loading of the DSO grid. Since no power-flow calculations are performed, this system-level constraint is implemented as an approximation using historical aggregate loading data. Under the calculated FCA, the total loading of the grid, including the new connection, will not exceed a specified percentile threshold of the historical total loading.

The starting point for this criterion is the maximum historical total load, which defines a value that should never be exceeded. To introduce a safety margin, a percentile of the historical total load is used instead of this absolute maximum. This percentile-based threshold lies below the maximum and therefore implements a conservative buffer, which is particularly relevant for load-side FCAs where the grid operator has no curative means such as curtailment or redispatch. The lower the chosen percentile, the larger the buffer; using the 100th percentile would correspond to the maximum historical total load and therefore to a threshold with no buffer.

For the total load criterion, the percentile is calculated over all timesteps of the historical total load time series. The corresponding power value is then used as the global total load threshold. In this work, the 98th percentile of the historical total load is selected as a compromise between utilizing existing capacity and maintaining a conservative margin. Figure 14 illustrates this by showing the daily total grid load (green lines) and the resulting 98th percentile threshold (yellow line).

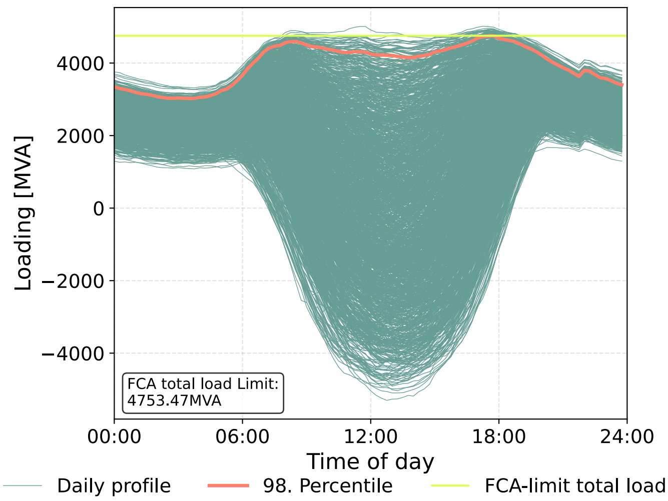


Figure 14: Aggregated, daily loading of all exemplary transformers

A clear seasonal dependence is visible in the historical data, as shown in Figure 15: the highest total demands occur during winter, while in summer the threshold is not reached at all.

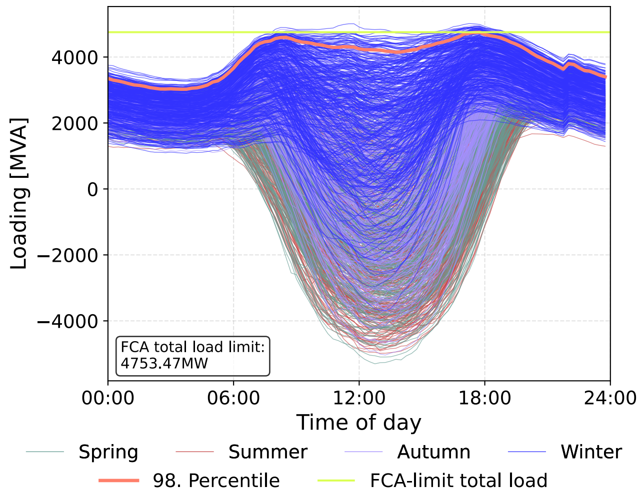


Figure 15: Aggregated, daily loading of all exemplary transformers in the Bayernwerk Netz area, shaded by seasonality

Figure 16 demonstrates how the FCA is extended by incorporating the total loading criterion. The FCA initially derived from local asset constraints is further restricted in all timesteps where the admissible power would otherwise cause the total grid loading to exceed the 98th percentile threshold. Consistent with the observed seasonal pattern, this additional limitation becomes relevant mainly during autumn and winter, and in extreme situations can result in FCA limits as low as zero admissible power for the connection.

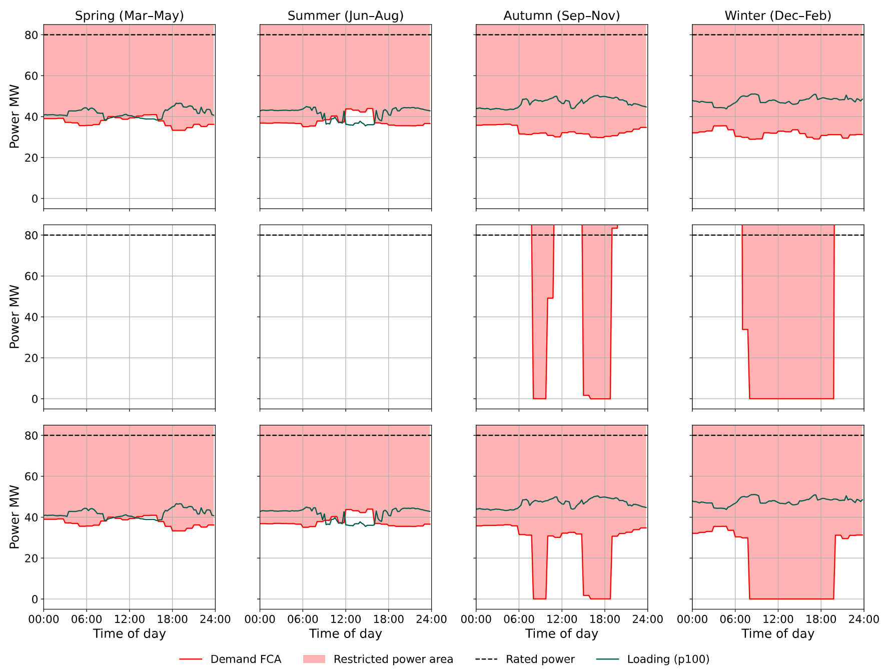


Figure 16: FCA including the N-1 criterion (top), FCA restrictions due to total loading (middle), combined restrictions for the demand FCA (bottom).

4.2.3. Evaluation of the demand FCA

Similar to the feed-in FCA, the demand FCA methodology is evaluated from both perspectives: the customer and the grid operator. The customer-side evaluation calculates curtailed energy based on the FCA applied to a constant demand profile, while the grid operator view sees the delivered annual energy comparing different connection methods.

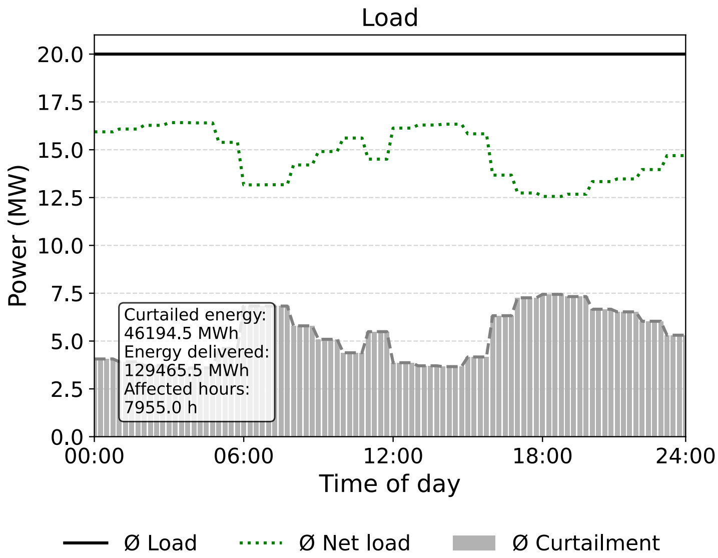


Figure 17: Energy constraining effect for the customer with a demand FCA on a 20MW band load grid connection request at the exemplary substation.

In this example, a 20 MW grid connection request is simulated at an exemplary 80 MW substation. Figure 17 shows from the customer side the residual load throughout the simulated year with the applied FCA. Due to the nearly constant limiting nature of the FCA, approximately 7,955 hours of the year are affected.

The grid operator view on energy delivered compares results across four grid connection setups:

1. **No restriction**
2. **Static capacity limit**
3. **Static control (PAV,b)**
4. **FCA-based connection**

The comparative analysis of grid connection setups is shown in Figure 18. Without restrictions, the customer could have drawn 175,660 MWh from the grid with a 20 MW connection. Under the classical method, the maximum available power at the substation would result in an 8.95 MW connection. Since the demand request is constant, both the setup and the scaled setup yield the same energy of around 78.6 MWh. In contrast, the FCA setup enables 65 % more energy compared to the classical methods while it still allows for up to the maximum requested power, highlighting the advantage of FCA determination over standard methods.

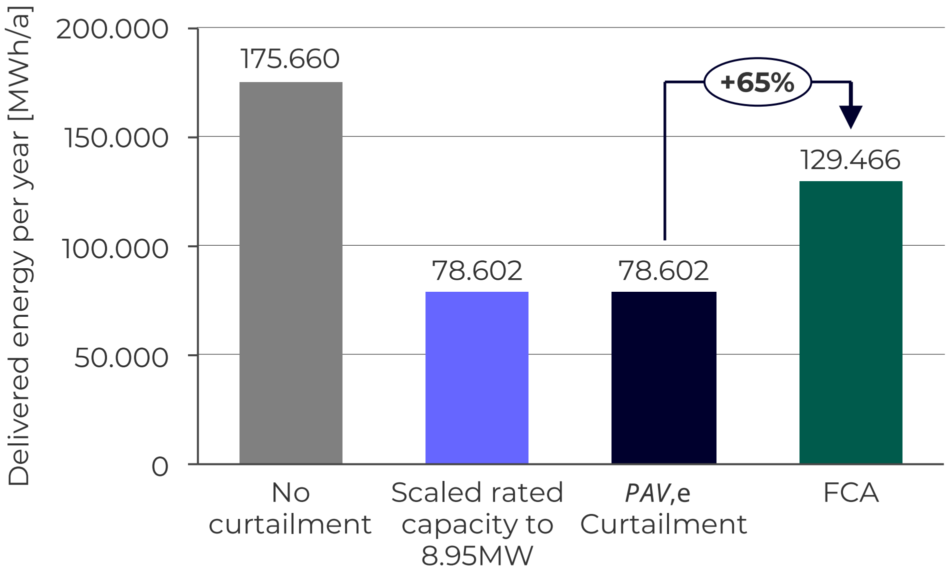


Figure 18: Comparison of grid connection setups for a load connection request of 20MW

To assess the impact of the new load connected under FCA on substation loading, Figures 19 and 20 illustrate the substation loading with the new grid connection request without and with FCA applied. Figure 19 (without FCA) shows clear overloads—shorter overloads in spring and summer and prolonged overloads in autumn and winter. Without an FCA, the connection request could not be accommodated within the existing operational headroom and would require grid reinforcement. Figure 20 demonstrates that the FCA effectively prevents overloading, ensuring compliance with operational limits.

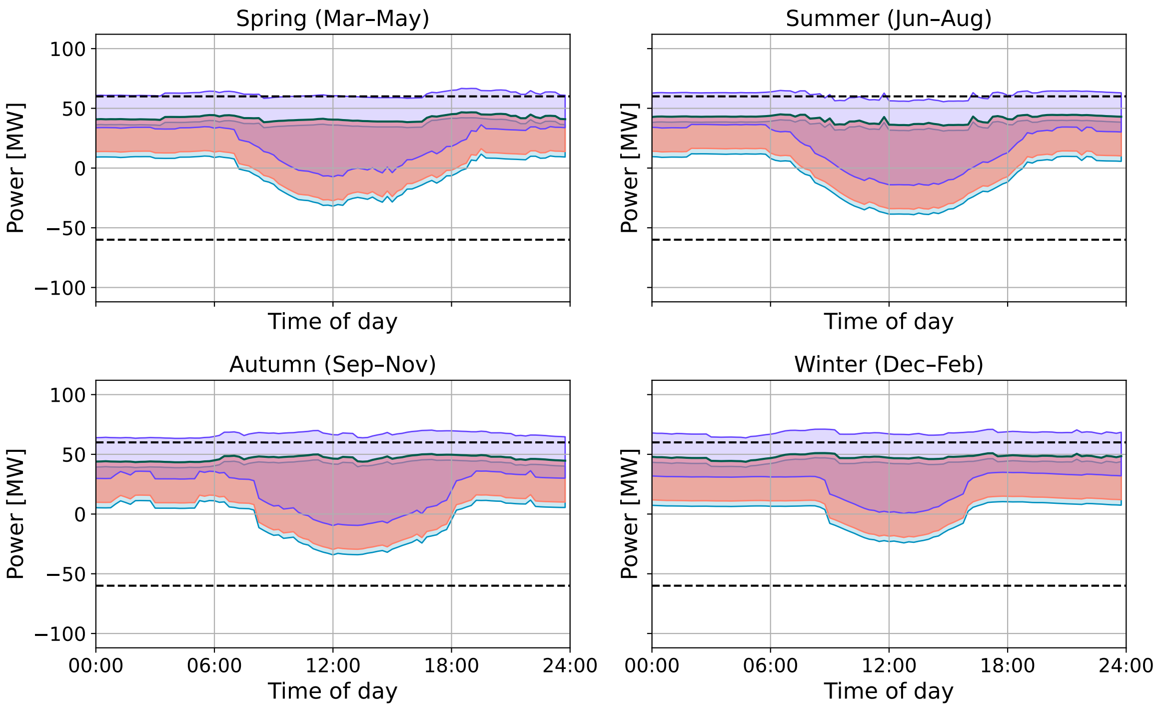


Figure 19: Additional loading of substation with the 20 MW grid connection request added without FCA.

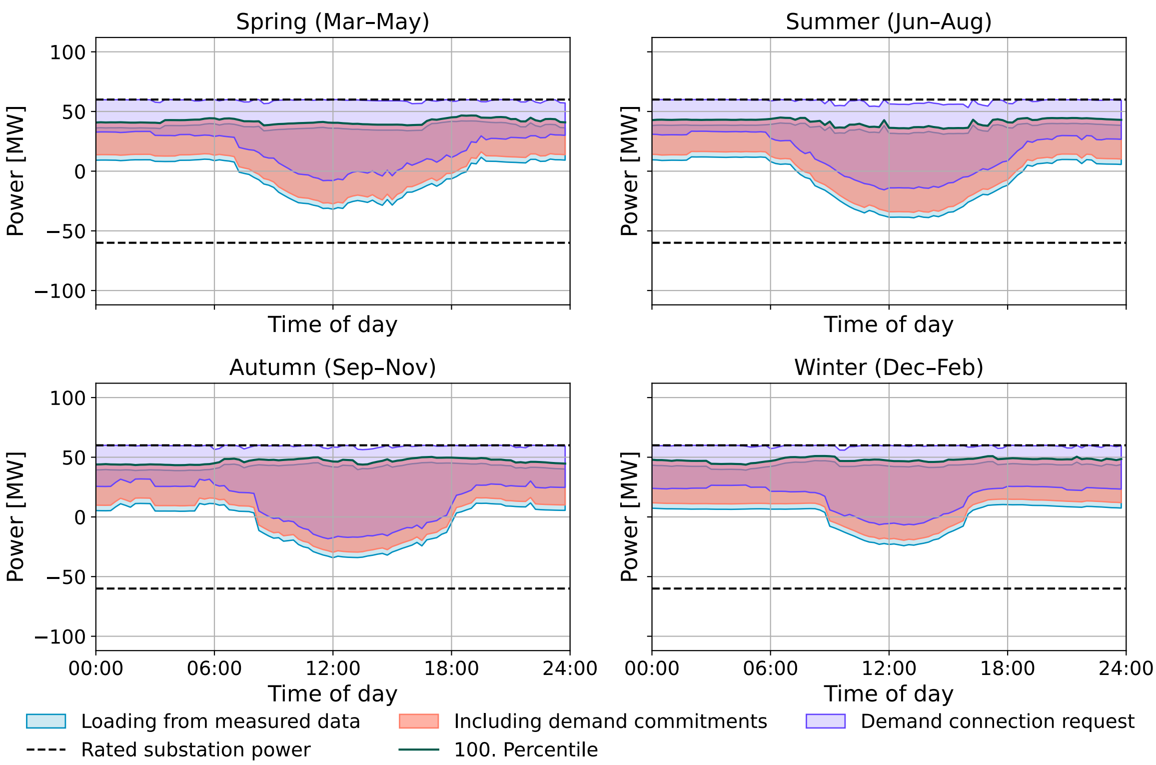


Figure 20: Additional loading of substation with the 20 MW grid connection request added under FCA.

5. Summary and future work

The methodology presented in this whitepaper introduces the first data-driven approach for determining Flexible Connection Agreements that explicitly addresses the operational concerns of grid operators rather than focusing on project developer perspectives only. By leveraging historical loading data and applying percentile-based logic, the model provides a transparent and reproducible framework for defining FCA limits at asset level. This approach enables grid operators to make informed decisions on conditional connections while maintaining system security. This allows the existing grid infrastructure to be utilized more efficiently and enables more customers to be connected to the network.

A key strength of the methodology lies in its ability to handle both feed-in and demand FCA calculations within a unified framework. This capability is particularly relevant for storage assets, which combine characteristics of generation and load. By integrating both perspectives, the model can support advanced FCA strategies for battery energy storage systems (BESS) and other flexible assets, ensuring optimal utilization of grid capacity without compromising reliability.

The evaluation demonstrates that FCA-based connections can significantly increase grid utilization compared to traditional static capacity limits or static control approaches. For asset owners, this translates into higher operational flexibility and improved economic performance, while grid operators benefit from reduced congestion and deferred reinforcement costs.

Future work will focus on several areas of refinement:

- **Enhanced synthetic profiles**: Improving the representation of demand and flexibility patterns to better capture customer-side behavior and variability.
- **Combined FCA strategies for hybrid assets**: Developing methodologies for assets that act as both generation and load, such as storage systems, to optimize their contribution to grid stability.
- **Integration of higher grid layers**: Extending the model to consider interactions with upstream networks and regional constraints.
- **Sensitivity-based optimization**: Automating percentile selection and buffer parameters to balance curtailment risk and redispatch requirements dynamically.

About P3

P3 energy solutions is a consultancy company centered around the energy transition, specialized in **Hydrogen, Power-to-X** and **Energy Systems**, combining decades of industrial experience with technological expertise and cutting-edge market knowledge.

Our customers value us as **trusted advisors** and **active participants** in implementing the **energy transition.** We provide tailored **solutions** from strategic, financial and technical consulting to operational implementation.

Our mission is to **bridge sectors** and **empower clients** through long-term partnerships with the tools, insights, and support they need to achieve their goals. We shape the future by guiding complex projects **from vision to execution**, ensuring that our clients succeed in dynamic, fast-evolving markets.

About Bayernwerk Netz

For 100 years, the name Bayernwerk has stood for **safe and reliable energy supply** in Bavaria.

As a **network operator**, Bayernwerk Netz GmbH plays a key role in fulfilling this mission. To ensure that increasing volumes of energy from renewable sources are available today and in the future, a modern and intelligent power grid is essential.

That is why the company focuses on digitalization and innovation, supports numerous scientific projects, and systematically works on expanding the energy networks.

Bayernwerk Netz GmbH **supplies energy** to around **seven million people**. It operates in the Bavarian regions of Lower and Upper Franconia, the Upper Palatinate, as well as Lower and Upper Bavaria, making it the largest regional distribution system operator in Bavaria. Its **electricity grid spans 156,000 kilometers**, its gas network 6,000 kilometers, and its street lighting network 34,600 kilometers.

Across its networks, **75 percent of the electricity distributed comes from renewable sources**. This is made possible by approximately 460,000 decentralized generation plants feeding renewable electricity into Bayernwerk's grid.

The company is headquartered in Regensburg. Bayernwerk Netz GmbH is a wholly owned subsidiary of Bayernwerk AG, which is part of the E.ON Group.

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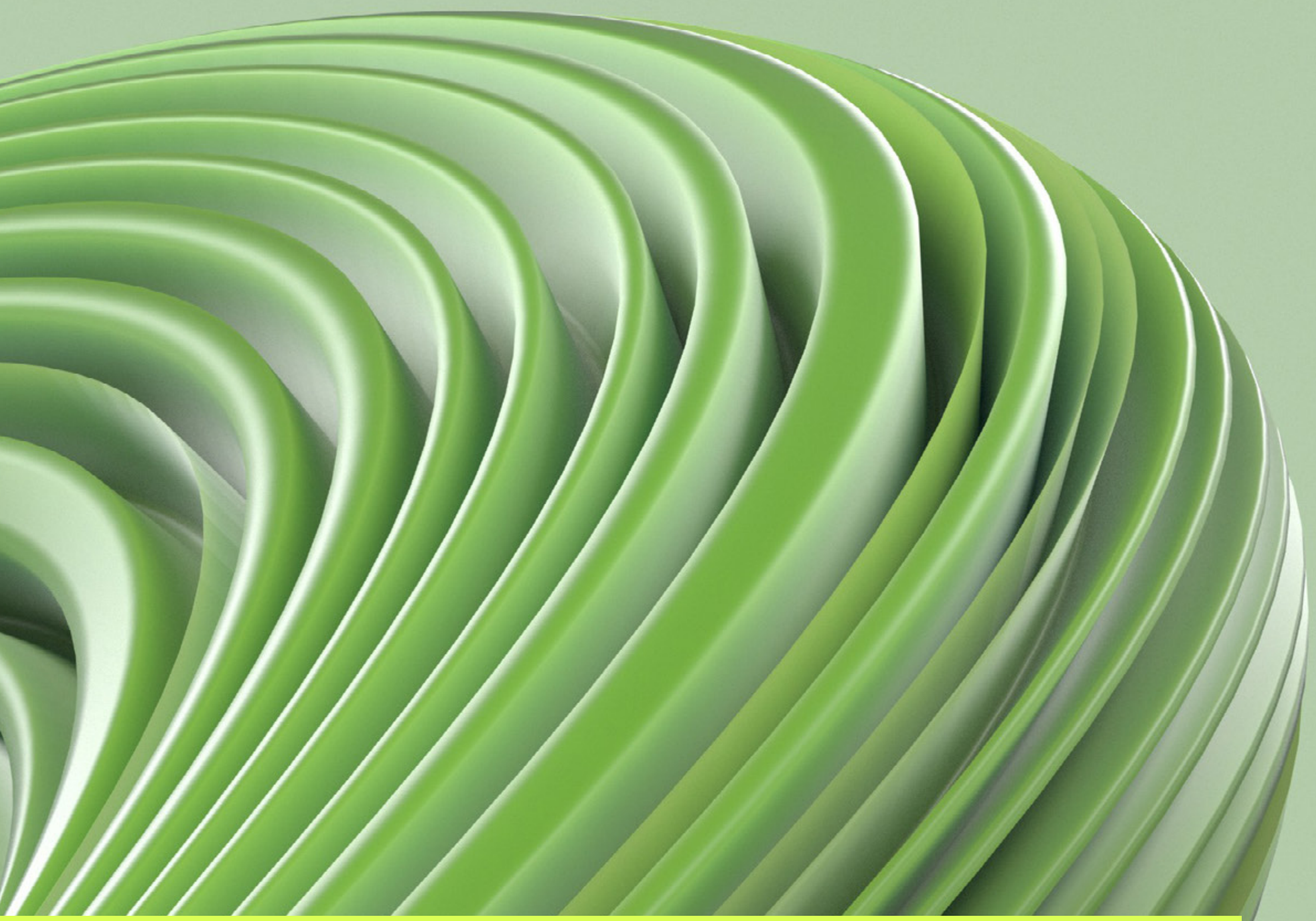

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