ARUP

The Ministry of Economic Affairs and Climate

Independent review on the FGU Region Grid Model

Arup report for EZK

Contents

ARUP

Executive summary

Executive summary

Background and reason for the study

The Dutch network operators report that the electricity grids are approaching their capacity limits in large parts of the country. Grid operators, central government and other authorities and parties are working together within the National Action Programme on Grid Congestion to accelerate grid expansions and to use existing capacity as efficiently as possible. The situation is most urgent in the provinces of Flevopolder (Flevoland excluding the Noordoostpolder), Gelderland, and Utrecht, i.e. the FGU region.

Since the end of 2022, the FGU region has been designated by TenneT (the Transmission System Operator, TSO) as a congestion area, and requests for transport capacity for any new large consumer connections have been put on a waiting list. A collection of measures has been identified by TenneT in conjunction with the Distribution System Operators (DSOs) and other key local stakeholders. Since early 2025, three calculation rounds: round 1, round 2, and round 3, have been performed to understand the impacts of these measures. The most recent calculation and results communicated by TenneT in round 3 show that the collection of measures, as modelled, would only be able to alleviate the situation to a certain extent, but not achieve full resolution of the congestion issues completely, as unacceptable overloads would remain. TenneT warns of the need for radical remedies in this area, in light of these results[1].

Introduction to the study

Given the major societal impact and policy implications, the Ministry of Economic Affairs and Climate (the Ministry) has decided to appoint Arup to provide an independent external review of TenneT's modelling.

The review covers the full modelling chain, including network representation, the changes in input data, assumptions, and treatment of flexibility. It analyses the evolution of TenneT's results across the calculation time, with focus on the latest two rounds of calculations, round 2 and round 3. The report is intended for the Ministry and other key stakeholders, and it provides an objective assessment of the modelling approach and the factors influencing recent results.

1 https://www.tennet.eu/nl-en/news/powerful-interventions-flevopolder-gelderland-and-utrecht-needed-prevent-connection-stoppage-small-scale-consumption

Aim of the study and focused research questions

This research seeks to offer a comprehensive analysis of TenneT's modelling of grid congestion in the FGU region, focusing on the modelling approach and key drivers behind recent results.

The following research questions are central to this and have helped shape the focus of the analysis.

Focused research questions

A. Net–gross effect of measures and the waterbed effect
These questions explore how flexibility measures that look at alleviating fluctuations in supply and demand, translate from gross volumes at the local level, into net congestion relief at the meshed transmission network level.

B. Natural Growth
The validation focused on factually identifying the key assumptions and then ascertaining what changed between calculation rounds.

C. Modelling of grid-supporting battery systems
These questions examine how grid supporting batteries are represented in the model and their impact on congestion outcomes.

D. Bottlenecks in line connections versus substations
These questions examine how bottlenecks are identified and assessed across different types of network assets, including both substations and line connections.

E. Sensitivity, bandwidths, safety margins and assumptions
These questions explore which sensitivities have been tested during the modelling rounds.

Our analysis focuses on factual, evidence-based observations and information provided by TenneT and key stakeholders. We focus on the validity of the model and main assumptions, and do not comment or make recommendations on any subsequent policy decisions that could be derived from the model's results.

Methodological approach

We undertook this review as external and independent advisors, drawing on our extensive international expertise in electricity networks, system planning and meshed network modelling. We also brought an objective perspective, being independent of previous discussions and decision-making processes, to provide an impartial assessment based on factual and evidence-based observations. Engagement with TenneT and other key stakeholders formed a central part of the work, enabling us to complete a detailed examination of the modelling framework, its implementation and its outputs.

The methodology was inquiry-based and centred on structured fact-finding, technical challenge and validation. It combined structured questionnaires, targeted Q&A sessions, bilateral discussions with DSOs and the regulator, workshops, and direct observation of live model execution. Within this framework, we examined a set of defined hypotheses regarding the drivers of variations between calculation rounds, while also developing detailed technical responses to the specific focus research questions. This ensured that the review addressed both the underlying causes of change in model outcomes and the specific areas of focus raised by the Ministry.

A fundamental working assumption underpinning the review is that TenneT and other stakeholders provided full, accurate and reliable information throughout the process. Given the confidential and security sensitive nature of transmission system data, our review did not involve rebuilding the model in a separate environment, and we have not independently verified the datasets. Instead, we obtained assurance through live observation, selective replication of results and consistency checks carried out in collaboration with TenneT. The work focused on understanding and explaining the key modelling assumptions and drivers underlying the results, and on forming an informed view as to whether the modelling approach, as applied, reflects current best practice within the agreed scope boundaries.

Responses to the research questions

In general, based on the assumptions and methodology followed, we consider TenneT's modelling approach to be methodologically technically valid, aligned with what we have observed in other network operators internationally. The results are coherent and reproducible. This report provides detailed answers to the focus research questions, and the main findings are summarised below.

A. Net–gross effect of measures and the waterbed effect

We observed that the modelling approach used to assess the net effect of flexibility is consistent with established practice for meshed transmission networks, relying on full load flow analysis rather than simplified netting or arithmetic aggregation. Flexibility is incorporated directly into hourly demand and generation profiles and evaluated within the power system model, allowing locational and temporal interactions to be captured explicitly, including the redistribution of power flows across assets (the waterbed effect). This framework accommodates successive layers of flexibility, from contracted gas-fired generation and DSO-level demand side measures to the explicit inclusion of large-scale batteries in later calculation rounds.

The effectiveness of flexibility is defined by the network topology, the temporal coincidence between demand and flexibility, and the location and availability of flexible resources. An apparent increased visibility of the gross-to-net effect in the most recent calculations is primarily attributable to the introduction and dispatch of a substantial volume of battery storage modelled as assets that are fully grid-supporting, rather than to changes in the underlying modelling methodology. Other simplified interpretations of flexibility impacts, such as one-to-one equivalence between flexible capacity and new connections, are shown to apply only under specific and constrained conditions.

B. Natural Growth

We investigated what assumptions and inputs underpin the treatment of Natural Growth, noting that demand forecasts are largely derived from DSO inputs and informed by energy transition scenarios, electrification trends and observed demand. DSOs report that, based on actual observed demand, total actual annual energy demand is flattening or declining in recent years, however peak demand continues to increase and remains the primary driver for system planning. This could be potentially due to uptake of heat pumps and non-smart EV charging. We found during our research that changes between calculation rounds primarily reflect refinements to these assumptions, including for example revisions to household connection growth.

C. Modelling of grid-supporting battery systems

Our review found that the principal change between the second and third calculation rounds was the introduction of a logical dispatch model for grid supporting battery systems. In earlier rounds, batteries were treated either as grid neutral, with no assumed charging or discharging during peak conditions, or purely market-driven, which showed worsening of grid congestions at certain points due to the fact that market-driven behaviour does not take into consideration local network congestions. In the third round, they were explicitly modelled to provide congestion relief. The dispatch logic assumes perfect foresight and operation aligned with system planning objectives, which we consider to be aligned with best practice.

Our analysis also showed that batteries were modelled based on actual connection requests currently in the connection queue, with assumed four hour energy capacity, which is technically consistent with current technology deployments. A key consideration is that the impact of grid-supporting batteries on congestion modelling outcomes depends materially on assumptions regarding control and operation. The assumptions adopted in the third round involve batteries being fully controlled by the TSO during periods of network constraints, rather than responding to market signals. We believe that this latter assumption is not reflective of current market arrangements and conditions, even if the technical model is valid (as is the case).

D. Bottlenecks in line connections versus substations

Our review found that bottlenecks in both substations and line connections are assessed consistently within the same load flow modelling framework, using asset ratings and impedances derived from operational data and asset management inputs. Overloads are identified by comparing simulated power flows against asset ratings, with differences in percentage overloads reflecting differing capacities of lines and substations. We did not find that there had been a change in modelling approach. We observed that changes in the relative prominence of line constraints can be explained by power redistribution effects inherent to meshed networks, as well as the fact that the different assets will have different capacities and therefore show a different percentage of overloads, which is expected.

E. Sensitivity, bandwidths, safety margins and assumptions

Our review examined the key input assumptions underpinning the modelling and the processes used by TenneT and the DSOs to quality control those inputs. A two stage quality assurance process is applied, with initial checks undertaken by the DSOs and a further review by TenneT to identify outliers or unexpected variations, providing a consistent framework for validating demand inputs across calculation rounds. We also reviewed how assumptions are translated into model parameters and how sensitivity is addressed within the modelling process. Demand forecasts are provided as hourly profiles based on energy transition scenarios and observed demand, while flexibility measures, batteries and gas fired generation are incorporated through explicit operational profiles reflecting congestion conditions.

Although formal sensitivity analyses are not documented as such, we observed that different calculation rounds, alternative battery modelling approaches and live testing of flexibility volumes, injection locations and PST settings function effectively as sensitivity tests, allowing the impact of key assumptions and parameters on congestion outcomes to be explored in practice.

Conclusions of the study

This independent review examined TenneT's modelling approach, the evolution of inputs across calculation rounds, and the drivers behind the outcomes observed in the round 3 calculations, within the scope defined for this assignment. The conclusions below reflect factual observations based on the information made available to us, the model demonstrations provided by TenneT, and the review methodology described in this report.

Modelling transparency and reproducibility

The modelling workflow demonstrated by TenneT was transparent and traceable within the scope of this review. Model re-runs observed during technical sessions reproduced reported results, and all technical questions raised during the review process were addressed by TenneT.

Consistency of modelling methodology

No material changes to the modelling methodology, meshed network modelling and representation, security criteria, such as N-1 requirements, or solver settings were identified between calculation rounds. The modelling approach applied across rounds was consistent.

Drivers of changes between calculation rounds

Our assessment indicates that differences between the outcomes of round 2 and round 3 were attributable to changes in input assumptions rather than changes in modelling methodology. The two main drivers of differences are the shift from Autonomous Growth (which includes new connections) to Natural Growth (which only accounts for growth in demand for existing connections) for demand forecasts, and the introduction of a dispatch model for large-scale BESS (Battery Energy Storage Systems) that assumes full TSO control for grid congestion relief.

Representation of meshed network effects

The waterbed effect and related gross to net impacts of flexibility were represented in a manner consistent with expected behaviour in meshed transmission networks. The distribution of power flow across the network follows the network configuration and the influence of asset characteristics, such as impedance, and existing loads in the network. The magnitudes observed are in line with general expectations for a network of this configuration and loading.

Assumptions regarding large-scale BESS

The modelling of large-scale BESS in round 3 as fully dispatchable by the TSO for the purpose of congestion relief, with perfect foresight and no losses, reflects a technically acceptable representation of the theoretical contribution of these assets. However, it does not fully align with how these assets currently operate within the Dutch electricity market as it does not take into account contractual or cost-benefit considerations. Therefore, the positive contribution on grid congestion relief achieved from BESS dispatch is likely to be overestimated under the current market operational arrangements.

Overall assessment

Within the scope of this independent review, no methodological issues or internal inconsistencies were identified in the modelling approach as demonstrated. The modelling behaviour observed was coherent and aligned with established practice for meshed transmission network studies.

Recommendations

The following recommendations reflect areas for additional clarification, documentation or scenario exploration. These points arise directly from observations made within the scope of this independent review and do not constitute policy advice or an assessment of the suitability of specific outcomes.

Reporting, Communication and Governance

– Develop standard KPIs and reporting

During our review, we observed differences in how key modelling parameters and outputs are presented across calculation rounds and stakeholder communications. We believe that agreeing a standardised set of KPIs (Key Performance Indicators) amongst key stakeholders, with clearly defined terminology and consistent application across calculation rounds, could support comparability and transparency in reporting. A set of standard reports using a common language and conventions would facilitate tracking and monitoring progress against the different measures that can be adopted and agreed. Such an approach would allow decision-makers and the wider community to understand the impact of the decisions and the evolution in time, for example when restrictions are expected to be lifted as progress is made towards resolution.

– Strengthen documentation and quality assurance for the model update process

While we received clear technical explanations during this review, it became apparent that the processes and quality assurance approaches are not always documented. We are of the opinion that it would be beneficial for TenneT and the DSOs to formally document the processes and procedures around these calculations, including any methodological improvements or changes. This would support long-term transparency and reproducibility.

Modelling of Battery Energy Storage

– Consider reflecting more realistic operational behaviour of large-scale BESS in future modelling

Representing batteries as fully dispatchable with perfect foresight provides a useful upper-bound scenario for assessing the potential contribution of BESS flexibility. Explicitly distinguishing such technical potential scenarios from assumptions aligned with current operational or market arrangements in future modelling exercises could support clarity in how results are interpreted.

– Consider what regulatory or commercial changes could enable full TSO control

We observed in the review that modelling outcomes for large-scale BESS are sensitive to assumptions regarding control and dispatch. For full TSO control to be realised in practice, regulatory or commercial arrangements would be required to secure availability, potentially involving contractual compensation for foregone market revenues. A full cost-benefit analysis of such a market-based alternative is recommended, to ensure that the final consumer received the optimal benefits from these decisions. Further regulatory routes could also be examined, including derogations permitted under existing regulatory frameworks (Article 54 of EU Directive EU 2019/944).

Section 1
Introduction

Section 1
Introduction

1

The Dutch electricity grids are approaching their capacity limits in large parts of the country. Grid operators, central government and other authorities and parties are working together within the National Action Programme on Grid Congestion to accelerate grid expansions and to use existing capacity as efficiently as possible.

The situation is most urgent in the provinces of Flevoland (excluding the Noordoostpolder), Gelderland, and Utrecht, i.e. the FGU region. From a transmission perspective, the FGU region is supplied by a single meshed 150 kV transmission network, which is connected with the 380 kV transmission network across four substations.

The congestion situation in the FGU region has constrained new large-consumer connections since 2022, when the area was formally labelled a congestion area and new transport-capacity requests began to be queued. To evaluate whether the proposed mitigation package would change that outlook, TenneT ran a series of dedicated congestion calculations. The latest results of these calculations do not show a full resolution: although the measures reduce the extent of loading problems, it does not remove them, and unacceptable overloads are still forecast.

Based on the outcomes of these new analyses, TenneT warns of a complete connection stop for the entire FGU region. This would mean that, in addition to large consumers, no new small consumer connections would be possible either, including increases in connection capacity for existing connections.

Against this backdrop, the Ministry of Economic Affairs and Climate (the Ministry) has decided to appoint Arup to provide an independent external review of TenneT's modelling.

We as Arup bring a strong combination of power system modelling insight, and techno-regulatory expertise. Our team has deep familiarity with the challenges of congestion management, model traceability, and the sensitivities inherent in highly interconnected grids. Drawing on our global work we are well positioned to deliver a concise, high-quality review within the timeframe required by the Ministry. We understand that the board of TenneT has committed to cooperating fully and to providing complete transparency regarding the models, calculations, and assumptions that they have used.

1.1. Objectives

The key objectives of our review are summarised below.

- Undertake an independent technical review of TenneT's congestion modelling for the FGU region, based on factual observations and information made available during the review process.
- Examine the modelling approach across successive calculation rounds, including testing a set of defined hypotheses to identify the drivers of changes in modelling outcomes.
- Provide technical assurance within the agreed scope and methodology, including review of model configuration, input assumptions, and treatment of flexibility.
- Respond to focused research questions, based on structured analysis, stakeholder engagement, and model demonstrations.

1.2. Structure of the Report

This report is structured as follows:

- The Executive Summary is designed as a summary report, providing enough information to understand the key elements of the study: background, methodology and findings, as well as the conclusions and recommendations.
- Section 1, this section, provides the introduction and structure for the rest of the report.
- Section 2 provides a summary of the congestion situations in the FGU region, TenneT's calculation rounds and their timeline.
- Section 3 outlines the approach for our independent review.
- Section 4 provides the detailed analysis the hypotheses included in our methodological approach, as well as the relevant findings.
- Section 5 addresses the focused research questions put forward by the Ministry.
- Conclusions and recommendations are presented in the Executive Summary section of the report, therefore not repeated again in the body of the report.

ARUP

Section 2

Background

Section 2
Background

2

This section focuses on establishing the background of the transmission network in the FGU region and its congestion situations in accordance with the calculations performed by TenneT.

2.1. Transmission Network in the FGU Region

The FGU region is served by a single meshed 150 kV transmission network (as seen in Figure 1), which exchanges electricity with the 380 kV transmission network at the following substations:

– Breukelen Kortrijk

– Lelystad

– Langerak (Doetinchem)

– Dodewaard

Figure 1 Transmission Network in the FGU Region.

Source: TenneT

2.2. Congestion Situation in the FGU Region

The overview of the congestion situations in the FGU region can be summarised in the following timeline:

- TenneT has anticipated congestion in the transmission network of the FGU region since November 2022.
- The official first congestion report was published in October 2023. At that time, TenneT already mentioned that this could affect connections of small consumers (i.e. Kleinverbruik) in the future.
- A collection of measures to manage the anticipated congestion in the FGU region was developed together between TenneT, the Ministry and key stakeholders, and they were announced in April 2024.
- Delays to transmission expansion (e.g. Utrecht Noord Substation) announced in June 2025, with a delivery date moved from 2029 to 2033-2035. This has significantly impacted the congestion forecasts in the area.
- Regarding the recent calculations, the first round of calculation for congestion was performed in September 2025, which underpinned the formal congestion assessment report published in December 2025.
- The second round of calculations for congestion was performed shortly after in October 2025, which underpinned the Letter to Parliament (also in October 2025) on the transmission congestion situation.
- The Distribution System Operators (DSOs) updated their demand forecasts between round 2 and round 3 of the calculations for congestions (between October 2025 and December-February 2026) by removing reservations for small consumers. This is referred to as a shift from Autonomous Growth (which takes into account certain new connections) to Natural Growth (which only include growth within existing connections). This is explained in more detail later in this report, in section 4.1.
- The third round of calculations for congestion was performed in the period between December 2025 and early February 2026, which included modelling of BESS operating fully for grid congestion relief, which led to the announcement of a potential stop to all connections in February 2026.

Timeline of TenneT Calculation Rounds

Due to the congestion situation in the transmission network in the FGU region, a number of calculation rounds have been performed. Note that there were initial calculations and analysis performed in 2024, when initial congestion-relieving measures were identified by stakeholders. However, three formal calculation rounds have been completed, as shown in Table 1.

Table 1 Summary of TenneT Calculation Rounds

Calculation Round	Date of Calculation	Key Assumptions	Measures for Congestion Management	External communications and context
#1	September 2025	Autonomous Growth as forecasted by the DSOs Battery Energy Storage System (BESS) was considered to be grid neutral, i.e. not affecting the congestion situations Current ratings for TenneT's assets Autonomous Growth as forecasted by the DSOs	Gas-fired power generators Phase Shifting Transformer Optimisation	This was the basis for the Congestion Assessment Report published in December 2025
#2	October 2025	Autonomous Growth as forecasted by the DSOs Battery Energy Storage System (BESS) was considered to be grid neutral, i.e. not affecting the congestion situations MaxLimit ratings for TenneT's assets	Gas-fired power generators Phase Shifting Transformer Optimisation Flexibility for TenneT's customers and mid-scenario measures for flexibility by DSOs' customers	This was the basis for the Letter to Parliament in October 2025
#3	December 2025 - February 2026	Natural Growth as forecasted by the DSOs MaxLimit ratings for TenneT's assets	Gas-fired power generators Phase Shifting Transformer Optimisation Flexibility for TenneT's customers and mid-scenario measures for flexibility by DSOs' customers BESS optimised to alleviate congestion	This was the basis for the announcement in February 2026

ARUP

Section 3

Methodological Approach

Section 3
Methodological Approach

3

This section describes our approach to completing the independent review, the scope boundaries and the steps followed in the delivery of this project.

Description of the methodology

Our approach to this independent review relied on comprehensive engagement with TenneT throughout the project.

Arup approached the review with a strong technical foundation, drawing on our extensive international expertise and knowledge in this field. At the same time, as independent consultants and external to previous discussions, Arup brings an objective perspective and provides unbiased insights, based solely on factual, evidence-based observations. This ensured that the assessment was comprehensive and impartial.

The independent review methodology was primarily observation- and inquiry-based centred on a rigorous fact-finding and technical assessment process. The core elements of this approach comprised the following:

- The use of detailed questionnaires, follow-up questions, and structured Q&A sessions to constructively challenge presentations delivered by TenneT and to seek clarification where required.
- Bilateral discussions with key stakeholders, including DSOs and the regulator (ACM), to capture a broad range of perspectives and insights.
- Direct, live observation of TenneT's modelling environment during model execution, allowing us to examine the technical implementation and underlying assumptions.
- In-person and online workshops, including Q&A sessions to further understand how the model operates and handles different inputs and scenarios.
- Live validation and replication of previously reported results for randomly selected assets, as a way to ensure the model produces consistent results.

A fundamental working assumption is that TenneT (and other stakeholders) provided full, accurate and reliable information at every stage. The option of replicating their modelling environment separately, as one important consideration is the highly confidential nature of a TSO's data, including from the point of view of national security, and the highly complex data security processes that would have been necessary to put in place for the independent reviewer to gain access to them. This was not considered proportionate or realistic under the timeframes needed for the results.

Methodological approach

Although the full model was not re-built by us in a separate environment, and confidential network data was not made available to us (for the reasons mentioned above), key information was indeed shared with us in order to allow us to complete this review, including detailed responses to a Request for Information (RFI) questionnaire, historical presentations and tailored presentations focusing on the areas of the review.

Our work involved conducting a structured and independent review of TenneT's load-flow modelling tools (PowerFactory and ODINA packages) and their associated outputs. We carried out our review in parallel with TenneT, observing their models in operation and examining both the technical detail and the assumptions that underpin them, with particular attention to the requirements of meshed network modelling. We examined how the models were applied to the specific characteristics of the FGU meshed grid and evaluated the consistency of results.

The focus of this process was to understand and explain the key drivers and modelling assumptions underlying the differences between these results (round 3) and those produced in round 2. Drawing on this analysis, we formed an informed view on whether the modelling approach reflects current best practice.

Scope boundaries

Arup's review is based on factual observations and evidenced discussions with key stakeholders. The scope of our work is closely shaped by the focused research questions received from the Ministry. We do not provide policy advice in this study in relation to the interpretation of the results produced by the modelling.

Workstreams

The remainder of this section describes the methodology we followed to complete our research. Arup followed the workstreams structure outlined in Figure 2.

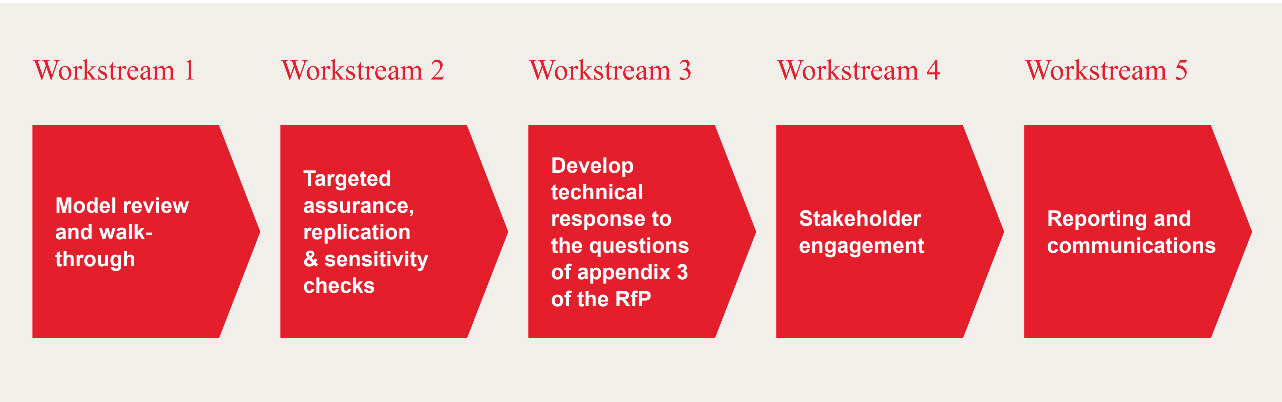

Figure 2 Approach workstream flow

Source: Arup

Worksteam 1

Model review and walk-through

This workstream aims to build a shared understanding of the main components that serve as the base of the model.

Understand Modelling Approach & Architecture

– Conduct structured walkthroughs of TenneT's end to end modelling workflow, with focus on meshed network representation, load flow configurations, forecasts, and interdependencies between model components.

– Review the modelling architecture:

  – How voltage levels are represented and whether any layers have been added, removed, or re-parameterised between runs.

  – How grid topology is captured, including treatment of coupling substations, line connection constraints, and dynamic behaviour across the meshed network.

  – Assess modelling assumptions around contingency definitions (N 1, N 2), headroom margins, and operational constraints.

  – How flexibility and battery systems are represented.

Identify key points where modelling decisions influence congestion patterns and test these against the observed deterioration in results.

Understand the Nature of Constraints

– Establish whether the network constraints that the model is returning relate to:

  – Thermal constraints.

  – Fault current levels/limits.

  – Upstream flows from the distribution network into the transmission network.

  – A combination of these elements.

Traceability & Change Detection

– Establish full traceability of modelling steps to identify and differentiate:

  – What changed between October 2025 (round 2) and the latest calculation.

  – Why the change was implemented (e.g., internal policy updates, external requirements, new data inputs, revised procurement deliverables).

– Use findings to categorise all changes into:

  – Methodology changes,

  – Input changes,

  – Network/safety requirement changes,

  – Other

– Ensure the traceability exercise creates a verifiable pathway linking changes to their quantitative impact on the model's outcomes.

Worksteam 2

Targeted assurance, replication & sensitivity checks

This workstream focuses on testing the three main hypotheses identified at project inception, together with targeted understanding of key areas of interest.

Hypothesis Testing Framework

A central component of this workstream is the development and application of a structured hypothesis-testing framework. This framework focused on three core hypotheses designed to identify the drivers of divergence between the October 2025 (round 2) modelling results and the current FGU outcomes (round 3).

Hypothesis 1

– Model Changes, including changes in modelling methodology (e.g., load-flow settings, solver tolerances, meshed-network treatment, modelling time intervals), changes in network topology, or other changes such as revised impedance data or asset capacities.

Hypothesis 2

– Input changes, including demand projections, generation forecasts, flexibility assumptions, grid-supporting battery deployments.

Hypothesis 3

– Network or Safety Requirement changes, including headroom/security margins, fault-current or short-circuit limits, maximum permitted loading of assets, N-1 / N-2 criteria,

In addition to testing the three main hypotheses above, the methodology also explores the following elements:

Flexibility Procurement Impacts

Looking at how assumptions about procurement of flexibility-providing services are incorporated into the modelling. Flexibility, in this context, covers the ability to adapt, or flex, the load profile of an asset or group of assets to provide a service to the network.

Spatial vs Temporal Waterbed Effect

A further area of analysis focuses on whether the observed waterbed effect (explained in section 4.4 later in this report) reflected spatial and temporal behaviour appropriately[2].

Explore Process for Model Update

Understand what procedure is followed to understand the model re-runs, and how consistency is preserved.

Model Reproduction & Sensitivity Runs

Reproduction of selective October 2025 and current model runs, working together with TenneT. This serves as a means of validating the modelling approach, however it would require access to TenneT’s model and specialists.

2 Spatial effect refers to situations where congestion relief applied at one location in the meshed network results in a power flow redistribution in other locations, driven by network topology and impedance-driven flow paths. Temporal effect refers to situations where congestion shifting is in time axis, e.g. congestion relief is effective in certain hours but leads to congestion re-emerging in other hours, due to flexibility is not available, sustained, or coincident with the system peak at the most critical times.

Worksteam 3

Develop detailed responses to the focused research questions

This workstream focused on addressing the specific set of technical questions, which fall within four main themes, as described below. Section 5 goes into the detail for each of the questions analysed.

A. Net–gross effect of measures and the waterbed effect,

B. Natural Growth,

C. Modelling of grid-supporting battery systems,

D. Bottlenecks in line connections versus substations, and

E. Sensitivity, bandwidths, safety margins and assumptions.

Worksteam 4

Stakeholder engagement

Given the compressed delivery timeline, stakeholder engagement was designed to be highly targeted, efficient and limited to those parties essential for validating modelling assumptions and understanding the drivers of change. The focus was on rapid clarification, informed challenge and ensuring that key insights emerging from the modelling review were tested with the subject matter experts.

Worksteam 5

Reporting and communication

This workstream focuses on synthesising and communicating the findings from the review.

ARUP

Section 4

Findings and Analysis: Model, Hypothesis and Processes

Section 4
Findings and Analysis: Model, Hypothesis and Processes

4

This section of the report first presents the overall modelling approach and architecture adopted by TenneT, as well as the nature of the constraints observed in the transmission congestion. Afterwards, this section details the findings in relation to the three main hypotheses that we have detailed in section 3, flexibility procurement impacts, waterbed effect, process for model update, and reproduction of model outcomes.

We would like to point out that, as our methodology is dependent on the information obtained from TenneT and other stakeholders, throughout the delivery of this project, none of our questions, whether raised verbally or in writing, were left unanswered. Equally important as reviewing the model itself was developing a clear understanding of the assumptions behind it, which we achieved through iterative discussion and reference to existing materials rather than ad-hoc explanations. On this basis, and contingent on the accuracy and completeness of the responses provided by TenneT and other stakeholders, we have confidence in the validity of our assessment. We have no evidence to suggest that the information supplied was incomplete or misleading, and nothing during the process raised concerns about the approach followed by TenneT.

4.1. Understanding of the Modelling Approach

The Energy System Planning department within TenneT employs a national PowerFactory grid model encompassing all circuits, substations and transformers in the Netherlands. This model is maintained and routinely updated by the Grid Model Management (GMM) team.
It comprises three components:

– Network data, representing the current grid, with circuit impedances derived from measurement reports and asset ratings provided by the Asset Management department.

– Network variations, capturing planned grid expansions with their expected in-service dates (ISDs), covering both designed and under-construction assets. Impedances are calculated based on conductor type, cross-section, length, and, for underground cables, installation configuration, whilst supplier data sheets also inform these calculations.

– Operation scenarios. Predefined study cases in the GMM model combine network data, variations and a selected operation scenario.

At the outset of each congestion study, the latest GMM model is duplicated and adapted through several steps, including:

1. Project planning for the FGU region is reviewed, and annual study cases are created based on updated ISDs. The congestion study methodology incorporates grid expansions in line with their ISDs.
2. Grid topology is verified, and additional study cases are developed where alternative topologies are required.
3. Current asset ratings were cross-checked against the latest MaxLimit dataset. For the calculation rounds 2 and 3, recalculated ratings are implemented as a network variation to support different calculation needs.

Once the PowerFactory model is properly configured, the ODINA tool reads the selected PowerFactory model, applies the relevant modelling settings, executes the load-flow analysis, and produces the corresponding results. The ODINA tool is the software package used by TenneT to perform the load-flow calculations via the efficient DC load-flow technique for the 150 kV transmission network in the FGU region for each of the 8760 hours in the years which are calculated. Further comparisons for specific hours were undertaken using the same demand forecasts imported into PowerFactory. These checks confirmed alignment between ODINA and PowerFactory load-flow outputs.

4.2. Nature of the Constraints

TenneT has performed load-flow calculations for the transmission grid in the FGU region using demand forecasts from both the DSOs and TenneT. This approach provides a realistic view of load patterns, including peak demand and periods of high loading. The calculations assess compliance with the N-1 security criterion, ensuring that the unplanned outage of any single 150 kV circuit or 380/150 kV transformer should not lead to assets exceeding their limits or to supply interruption. Outages of busbars or gas-fired generators are not considered.

Fault currents are not explicitly calculated for these congestion studies. These are assessed separately for TenneT's investment planning for grid expansion, and the results are reported in the congestion documents. In congestion studies, protection requirements related to fault-current limits are reflected indirectly through the modelled grid topology, which restricts the number of permissible configurations.

In summary, the nature of the congestion observed in the studies is thermal constraints: potential asset overloading against its applicable thermal rating.

Hypothesis 1: Model Changes

The first hypothesis focuses on any change to the transmission network model between different calculation rounds. In this regard, three main points have been reviewed, which are summarised as follows:

- We were able to confirm that the modelling methodology, its principles and network parameters have not been changed between round 2 and round 3. The only change related to network assets in the model occurred between round 1 and round 2, where updated asset capacities were used in round 2 and subsequent round 3, reflecting the MaxLimit programme. This means that the load flow settings, solver tolerances, network topologies, modelling time intervals have been consistent for all calculation rounds.
- We observed that the transmission network modelled has been the meshed 150 kV grid in the FGU region including its four interfacing substations with the 380 kV transmission grid. In other words, the transmission network representation (including the optimisation of the Phase Shifting Transformers, PSTs) has been the same, unchanged.
- We confirmed that the transmission network data (including impedances, network topology) and variations (or planned grid expansions) have been modelled the same throughout the calculation rounds.

Hypothesis 2: Input Changes

The second main hypothesis focuses on any change to the input data used between the calculation rounds 2 and 3. There are two critical changes to the input data identified in the review. These include:

- The Autonomous Growth assumption used in round 2 has been reduced to a Natural Growth assumption used in round 3 (see definitions below). Natural Growth is a demand forecast significantly lower than Autonomous Growth. This has been supported by DSOs through their updated demand forecasts. Comprehensive definitions of these two terms are included below:
  - Natural Growth: This is a demand forecast that only includes an increase in demand coming from two sources: existing connections and future connections that already have a legally-binding connection offer. For existing connections, increased demand is accounted for in the forecast, as long as this increase can be accommodated within existing connection capacities. Under this scenario there is no growth from new housing or EV charging stations or from energy-efficiency upgrades of existing housing when an increase in their connection capacity (in the low voltage network) is necessary for these upgrades.
  - Autonomous Growth: This is a demand forecast that incorporates the Natural Growth described above, as well as reservations for new connections for small consumers. This demand forecast includes connection capacity for new build houses, public EV charging stations, and energy-efficiency upgrades of existing housing.
- BESS is assumed to be fully controlled by TenneT for alleviating congestion in Round 3, whereas Round 2 assumes BESS is grid neutral, i.e. profiled at zero. This has been implemented through a BESS optimisation tool developed together with Stedin for Round 3.

The other input data (e.g. flexibility measures adopted) remains the same for both calculation rounds 2 and 3.

In summary, the main changes to input data have been significantly lower demand forecasts (i.e. lower peak demands at substations) and optimised BESS operation for alleviating congestion. These changes have led to improvement in the congestion situations observed in modelling outcomes, however, they are not sufficient to eliminate the congestion.

Hypothesis 3: Network or Safety Requirement Changes

The third hypothesis focuses on any change to the network or safety requirements captured by the model across the calculation rounds.

The main network security criterion of an N-1 requirement has remained identical across all calculation rounds. No relaxation or tightening of contingency definitions has taken place. N-2 or N-k situations (i.e. operational N-1 during maintenance, grid reinforcements or long-term asset unavailability) were not included.

The limits related to fault currents and short-circuit levels, have remained unchanged throughout all calculation rounds. There have been no changes to the fundamental network or safety parameters used in the analyses.

Nonetheless, it is noted that the recalculated asset ratings provided by the MaxLimit Programme have been used in both calculation rounds 2 and 3. Updating these asset ratings represents a refinement of the network data and does not entail a change to the safety criteria. Additionally, incorporating the recalculated asset ratings in the network model (starting from 2029) could be an optimistic assumption, ahead of the formal Electromagnetic Compliance (EMC) assessment being completed (the current EMC limits prevent TenneT from actually increasing their current asset ratings to these recalculated values).

4.3.Flexibility Modelling and Impact

The main flexibility provisions modelled by TenneT include:

- Gas-fired power plants
- Large-scale BESS
- Flexibility provisions implemented in the DSO grids (e.g. demand side response).

Detailed description of the modelling of these flexibility measures and their impact is provided below.

Gas-fired Power Plant Redispatch

The gas-fired power plants are directly connected to the 150 kV grid in the FGU region, and they are located close to the different 380/150 kV transformers. The need for flexibility provisions from these power plants is based on the load profiles of these transformers.

The gas-fired power plants have been contracted by TenneT to provide congestion management. Therefore, the model always implements their flexibility first. In summary, when the asset rating of the closest transformers is exceeded, a linear model using a power transfer distribution factor (PTDF) is used to assess the amount of flexibility needed. This amount is then incorporated into the generation forecast profile of the gas-fired power plant. After these new generation profiles have been generated, a full load flow calculation with these adjusted generation profiles is performed. In this load flow calculation, the phase shifting transformers (PSTs) are also optimized based on the new load flow, ensuring that the most favourable load flow is determined while taking into account the meshed-network effects.

BESS Optimisation

The third calculation round has used large-scale BESS to reduce the remaining grid congestion. A total of 965 MW of BESS capacity is included in Round 3, and the majority of the BESS capacity is expected to become operational around 2029. The locations of these BESS installations are based on existing capacity requests made to either TenneT or the DSOs. In other words, these systems are not necessarily located at the most effective points in the network to relieve congestion on the critical assets (i.e. the sensitivity of BESS location to its effectiveness for alleviating congestion suggests: if the location is closer to the location of congested assets then the effect is greater, than if the BESS is located far away, essentially due to the waterbed effects which will be described in section 4.4). The model assumes batteries are 4-hour systems, in the absence of actual storage energy capacities (TenneT and the DSOs only have information of the requested power connection size, i.e. BESS power capacity). Small-scale batteries (e.g. neighbourhood or home batteries) were not modelled, although they may be relevant for later local measures at the DSO level.

The modelling used the following assumptions to test the technical potential of BESS:

- Full control by TenneT,
- No energy losses (assumed roundtrip efficiency = 100%, whereas in reality ~90%),
- Perfect foresight of overload patterns,
- In hours for which the battery is not required by TenneT the load profile is assumed to be 0.

These assumptions mean that the model is to understand the theoretically maximum contribution of BESS to congestion relief. Particularly the first assumption of full control, TenneT recognises that this is not realistic under current market design and conditions. The assumption was deemed to be a theoretical exercise assuming perfect contractual conditions and not accounting or optimising for costs (as the modelling is purely technical-focused).

To optimise BESS operation, a congestion relief algorithm was developed together with Stedin (one of the DSOs in the FGU region). The algorithm aims to minimise the maximum overload on the assets at which it is targeting. The state-of-charge is tracked continuously to make sure a BESS is only available if sufficiently charged.

The profile of a BESS depends on the magnitude and duration of the overload. The following rules are followed:

- Short overloads: BESS provides exactly the needed power to resolve the congestion or its maximum rating
- Long overloads: discharge power is spread out to minimise peak overloads if the total capacity is insufficient to relieve the entire congestion period
- Multiple overloading assets: discharge power is allocated to minimise relative (percentage) overload
- For consecutive congestion events, congestion periods are addressed sequentially as follows:
  - Use all available energy in the first overload period
  - Charge when possible
  - Use energy again in the next overload period, and this process is then repeated
- Multiple battery systems:
  - Batteries are optimised one by one
  - After each optimisation, asset profiles are updated using a linearised impact model (i.e. PTDF)
  - The order in which the batteries are dispatched to discharge into the grid, both in terms of timing and location, is chosen in such a way that they provide congestion mitigation in the most effective way.

Flexibility Provisions

The flexibility provisions are implemented both in the DSO level and at the TSO level. To model flexibility provisions at the DSO level, TenneT shared load flow profiles of key assets with the DSOs, which subsequently modified their demand forecasts to include the available flexibility provisions at these moments of congestion (such as reduced EV-charging). The DSOs developed three scenarios for these flexibility provisions, labelled low, medium and high, of which the medium scenario was chosen by the DSOs to be modelled in TenneT's congestion study. The modelling for these modified demand forecasts was performed by the DSOs. TenneT also included its own flexibility provisions provided by large consumers in the relevant demand forecasts. As mentioned in the section 3, commenting about the suitability of assumptions behind demand forecasts and flexibility is outside of the scope of our independent review, these assumptions are typically more policy-driven than purely technical. Our review of the overall modelling approach and scenarios did not raise any specific technical concerns.

4.4.Waterbed Effect

In a meshed transmission network, the waterbed effect describes the non-local and distributed nature of load flow distribution across the network. For instance, when a transformer becomes overloaded, reducing demand at a remote load does not translate directly into an equivalent amount of reduction in loading on that transformer. Instead, due to the multiple parallel paths and impedance-dependent load flow distribution governed by network topology and impedances, only a fraction of the curtailed demand contributes to relieving the congestion on that transformer. In the PowerFactory model, the waterbed effect is represented by the calculation of the Power Transfer Distribution Factors (PTDFs).

Waterbed effect shows that in order to achieve a net reduction in the overload of an asset, a higher (gross) change in peak load (flexibility) is required depending on location. Some substations are more effective than others and TenneT has graded them in the Breukelen-Kortrijk (BKK) example based on the effectiveness percentage, which can be seen in Figure 3.

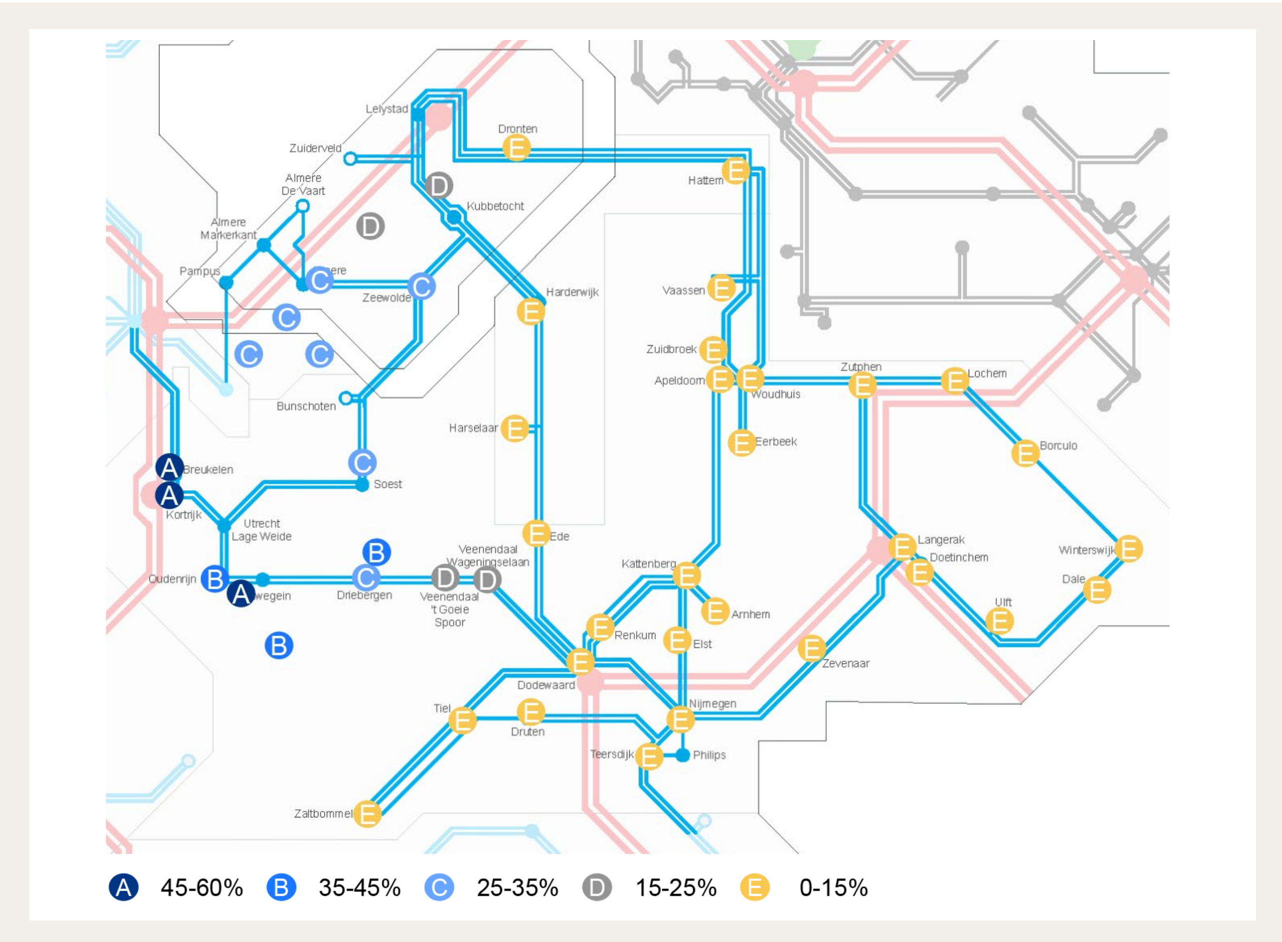

Figure 3 Effectiveness of flexibility at each substation on BKK transformer bottleneck.

Source: TenneT

Table 3 Waterbed effect on BKK transformer

100 MW Flexibility at	Effect on BKK (MW)
Breukelen	45 – 60
Zeewolde	25 – 35
Zaltbommel	0 - 15

For example, as seen in Table 3, if a flexibility provision reduces the demand at Breukelen Substation (a 150 kV to DSO substation) by 100 MW, the subsequent reduction in overload at BKK (a 380/150 kV substation located upstream to the previous Breukelen Substation) is between 45 and 60 MW, less than the 100 MW seen downstream. Similar effects are presented for Zeewolde and Zaltbommel Substations in Table 3 as well. To reiterate and further help clarity: Breukelen Substation is a 150 kV to DSO substation, whereas Breukelen Kortrijk (BKK) substation is a 380/150 kV substation.

4.5. Process for Model Update

A model update or scenario is a new calculation round by TenneT that adjusts demand forecasts and, if necessary, the grid model to match scenario assumptions. The grid model underpins all following steps.

The modelling process begins when updated DSO demand forecasts are received through SharePoint in the agreed format, providing hourly projections for each 150 kV substation. TenneT and the DSOs are working to automate this exchange further.

Upon receipt of demand forecasts from the DSOs, these are consolidated with TenneT's customer forecasts and integrated into the scenario template. The grid model is subsequently calibrated in accordance with the scenario assumptions. If the scenario necessitates modifications to the grid model, a new study case is established in PowerFactory, relevant network variations are applied, and the operational scenario is revised accordingly. Frequently, model updates primarily involve the inclusion of updated demand forecasts, while changes to network configuration are implemented as specified by the scenario requirements.

When the demand assumptions and grid model are ready, load flow calculations are performed to evaluate how assets are expected to be used throughout the year. The results are then checked for accuracy, which may include comparing them with previous scenario rounds to confirm long-term consistency, as well as reviewing the overall patterns in the yearly profile for internal logic. If any unusual trends or discrepancies emerge, they are examined closely to determine if they indicate shifts in system behaviour or problems with the input data or modelling assumptions.

4.6. Model Demonstration and Sensitivity Runs

TenneT has provided live demonstration of the model including both the PowerFactory model and the ODINA software package, during both the in-person session in their office and a follow-up remote session via MS Teams. The demonstration followed the typical process of congestion studies. In summary, the demonstration has covered the example calculation runs that re-produced the congestion situations reported across the three calculation rounds, providing validation and transparency of the model and their outcomes.

Further, live demonstration of load flow control via PSTs and waterbed effect was performed by TenneT during the technical sessions with Arup. Load flow re-distribution was observed with the change of PSTs tap positions. Examples of waterbed effect based on the substations in Table 2 were demonstrated, as follows.

- A 100 MW flexibility provision was added to Breukelen, consequently the PowerFactory model showed a reduction of 50.5 MW on the BKK transformer loading.
- A 100 MW flexibility provision was added to Zeewolde, consequently the PowerFactory model showed a reduction of 27.5 MW on the BKK transformer loading.

Additionally, Arup requested a demonstration of sensitivity check between AC and DC load flow calculation techniques. In short, DC load flow is a linearised calculation technique typically used for long-term network planning, whilst AC load flow calculation technique captures more power system characteristics and better represents the real conditions of the network. In the context of congestion studies, the inclusion of reactive power flows and transmission losses in the AC load flow calculation can lead to higher asset overloading conditions. The following observation is recorded during the demonstration, which reflects the expected difference in results.

– For the same scenario setup, DC load flow resulted in a loading level of 96% on the BKK transformer, whilst the loading level of the BKK transformer increased to 100% in the AC load flow calculation results. The difference of 4% is within the expected range for typical difference between AC and DC load flow calculations.

ARUP

Section 5

Response to Focused Research Questions

Section 5
Response to Focused Research Questions

5

This section addresses the specific questions listed in the Request for Proposal (RfP) received from the Ministry. We have included the initial opening framing paragraphs included in the RfP as text boxes in italics, to aid context.

5.1. Net–gross effect of measures and the waterbed effect

Research Question 1

"The effectiveness of flexibility has proven to be lower than initially assumed. In 2024, a target of 450 MW of flexible capacity was established, based on the expectation that this would prevent overloads in the FGU region. This target is expected to be achieved, provided that the measures are actually implemented in the coming period. However, the new model outcomes from TenneT show that flexible capacity is only limitedly effective in mitigating bottlenecks. In the models, 1 MW of flexible capacity results in only 0.2–0.4

MW of relief at a high-voltage substation. TenneT cites the meshed nature of the grid as the cause ("waterbed effect")."

5.1.1. How is the net effect of flexible capacity calculated in the model?

In summary, the effect of flexibility is assessed in the model with a full load flow calculation in the power system model. All relevant flexibility provisions are incorporated directly into the hourly demand profiles for each individual substation (this was performed by the DSOs and TenneT for their respective customers). This ensures that all meshed-network effects, such as power flows over different pathways and the net effect on bottlenecks, are fully captured. Note: a netting-off demand vs. BESS flexibility is not done ahead of inputting the data in the model, but instead the model is optimised with these two sets of data separately, taking into account locational effects as well as temporal effects – this is as expected. [In other words, the model was run with hourly demand profiles incorporating flexibility provisions; this run provided initial overloading conditions without BESS; afterwards, BESS would be optimised to minimise the overloading on assets taking into account locational and temporal effects of BESS operation; the model was run again with both hourly demand profiles incorporating flexibility provisions as well as optimised BESS discharging and charging profiles to calculate the resulting overloading conditions.]

The first step for modelling flexibility is to incorporate outputs from certain gas-fired power plants generators in Utrecht and Lelystad, that are directly connected to the 150 kV grid and are located close to the 380/150 kV transformers. These plants are modelled following the flexibility need of the transformers closest to them. It is important to point out that these plants are available to TenneT for grid congestion relief, therefore we consider this to be a reasonable assumption. The output from the gas-fired generators, optimised as described, is then incorporated into the generation forecast profiles.

As a second step, a full load flow calculation is performed. In this load flow calculation, the phase shifting transformers (PSTs) are also optimised based on the new load flow, ensuring that the most favourable load flow is determined while taking into account all meshed-network effects.

The second and third rounds of calculations also included flexibility provisions in the DSO grids (these are typically smart EV charging and other Demand Side Response measures). The effect of these flexibility provisions was modelled by the DSOs themselves, using load flow inputs from the transmission system from TenneT.

The third round of calculation specifically incorporated large-scale BESS. A total of 965 MW of BESS capacity was included, of which most is expected to become operational around 2029. The BESS that were included in this analysis were based on existing capacity requests at either TenneT or the DSOs. The model assumed batteries are 4-hour systems in order to calculate the energy storage capacity. With this assumed power rating and energy capacity providing a favourable load profile for congestion relief is computed for each of the BESS. The key assumption is that batteries can be dispatched by TenneT for grid congestion relief, without intervention from the asset owner. As we will discuss in the conclusions and recommendations, although the technical principles behind this modelling approach are reasonable from a technical point of view, the view is not considered realistic from a commercial and market design point of view.

In terms of the waterbed effect, the model produces outcomes related to the resulting power flows in the network, taking into consideration the interconnectivity of assets, the different asset characteristics and the local load at the multiple locations, resulting in the effect of flexibility to be split across various network components, which is an expected behaviour from meshed networks.

With regards to the flexible capacity target in 2024, TenneT has indicated that this capacity (475 MW was the accurate number) was indeed presented in spring 2024. However, they refer to this calculation as early analysis, with an additional factor that the delay of Utrecht Noord from 2029 to 2033 was not yet known. TenneT does acknowledge that their understanding of the area and their modelling tools have evolved, and also that the waterbed effect could have been communicated better, in hindsight.

5.1.2. What are the factors in the model that have an impact on the effect of flexibility?

In accordance with the steps for modelling flexibility, which is based on our understanding of the process and the information obtained from TenneT, the key factors that will have an impact on the effect of flexibility include:

- Topology and electrical parameters of the model: whether the model is an accurate representation of the real network. Our understanding is that it is.
- Model of how different flows behave on a time profile. This is known as coincidence factor (Gelijktijdigheid in Dutch) and takes into account the different timings for peak to occur in the system. Our understanding is that this has been taken into account by the demand profiles produced by the DSOs and TenneT for their respective customers.
- Location and availability (including speed of connection) for BESS and other flexible solutions. Our understanding is that this has been accounted for by modelling the BESS based on actual connection requests to TenneT and the DSOs, rather than preferred locations most effective for congestion relief.

It is worth noting that the impact of flexibility will depend not only on the technical model, but also on the assumptions made about the procurement and operation of the specific flexible solutions, which is relevant for how demand side response measures implemented by the DSOs as well as the large BESS flexibility are modelled (as mentioned above, it is an unrealistic assumption to assume full control from the TSO in this operation, unless very specific conditions are met).

5.1.3. What changed in the modelling compared with the second calculation round that made the gross-to-net effect more clearly visible in the third round?

There is no technical change in the modelling approach that made the gross-to-net effect more clearly visible in the third round, compared with the second round. Our understanding is that the reason for the perception that the gross-to-net effect is more clearly visible in the third round is that there is a large volume of BESS included in the third round (965 MW), whereas in the previous rounds, the volume of batteries was zero (effectively, modelled at zero profile during peak times in the network).

Figure 4 - TenneT's illustration of the waterbed effect (from an October 2025 presentation)

100 MW flex/belasting in	Effect on BKK (MW)
Breukelen	45 – 60
Zeewolde	25 – 35
Zaltbommel	0 - 15

One of the main changes in relation to flexibility between round 2 and round 3 was modelling BESS as fully dispatchable when it is advantageous for relief of network congestions. In round 1 and round 2 batteries were assumed to have a zero profile, whereas for round 3 a logical algorithm was implemented to model BESS (completed in early 2026), as described in section 4.3.

We have seen evidence of presentations from TenneT in October 2025 where the waterbed effect was being highlighted, for example in the figure below, which shows the effect of load reduction in the BKK substation by injecting 100 MW of flexibility in different areas of the network.

5.1.4. TenneT states that within a focus area, 1 MW of flexible capacity enables 1 MW of additional connection capacity. How plausible is that assumption given the gross-to-net effect? How is the aggregated effect of flexibility modelled?

We have asked a clarification question to TenneT on this assumption, as drafted in the question, as it does not match our understanding of the waterbed and net-to-gross effect that we discussed in the multiple workshops and Q&As. We understand that this specific message from TenneT is designed to be understood under very specific circumstances and conditions, and has been designed by TenneT as a simplification, applicable only to flexible solutions and capacity at the DSO level and only if this is enacted within the same TSO/DSO substation. Below a more detailed explanation.

TenneT's central idea is that, referenced against the baseline of current prognoses, in case 1 MW of additional load is connected at DSO-level to a TSO/DSO-substation and at the same substation also 1 MW of additional flexibility (e.g. dispatchable infeed) is connected, the net impact at the TenneT-level is zero. Note that under this assumption, the load profile of the flexible solution and the new capacity also have to coincide. Therefore, for this simplification to be true, a number of conditions need to be met, in regards to location (new capacity and new flexibility need to be in the same vicinity under the same TSO/DSO substation) and in regards to load profile (peak flexibility need to coincide with peak load in time).

TenneT asserts that this simplified principle is designed to enable stakeholders to steer the realisation and implementation of additional flexibility to those locations where it is required. TenneT states that, as a general principle, this was proposed as a simplification to enable stakeholders to steer the development of flexibility to the right locations at the local level. This is still under discussion with key stakeholders in the region. We believe that communication and clarity on what these numbers represent is key in ensuring full understanding and avoid simplifications to be quoted without context, and unintentionally misinterpreted.

With the exception of the specific simplification above, in terms of modelling the aggregated effect of flexibility is not being modelled as an arithmetic sum of the different individual flexibility measures.

We also think that there may have been presentations from TenneT in the past that included an arithmetic sum, potentially for illustrating how much total flexibility was included in the measures. See, for example, the figure below, which was included in the TenneT presentation to the Focus Group meeting on 10 March 2026 in The Hague. This table shows an arithmetic sum of the different measures in the collection of measures. It, however, relates to the input on these measures, which are then implemented in the load profiles and the grid model. This modelling then leads to exceedances observed in the load flow model. The arithmetic sum can be argued to show the gross input assumed on the size of the measure, not on the net effect on decreasing overloads.

3 Technically, under very limited conditions and if certain variables fully align, 1 MW of flexible capacity at the distribution level combined with 1 MW of new connection at a different location also at the distribution level could have a net effect of zero at the transmission level. However, these interaction effects do require analysis through TSO modelling.

Measures FGU calculation round 3

- The prognosis of the collection of measures was 645 MW (2nd round of calculations, based on autonomous growth). In calculation round 3, the prognosis of the collection of measures based on natural growth is 1224 MW, of which 965 MW is batteries.
- With natural growth, the extra yield of grid-aware charging and grid-conscious new construction is eliminated.
- Measures that were not included in calculation round 2 were also not included in calculation round 3.
- Realised to date: 43 MW measures.

Measures (MW)	2026				2029				2033			
	F	G	U	Sum	F	G	U	Sum	F	G	U	Sum
Congestion Management	-	9	13	**22**	-	9	30	**39**	-	9	30	**39**
Technical interventions	(20)	-	50	**30**	(20)	-	50	**30**	(20)	-	50	**30**
Reduce loopflows	-	-	-	-	-	-	-	-	-	-	-	-
Shift EV charging	-	-	8	**8** ↓	-	-	9	**9** ↓	-	-	9	**9** ↓
Temporary gas turbines	-	-	29	**29**	18	30	57	**105**	34	30	57	**121**
Net-conscious installations	-	-	-	- ↓	-	-	-	- ↓	-	-	-	- ↓
Net-conscious construction	-	-	-	- ↓	-	-	-	- ↓	-	-	-	- ↓
High asset rating	10	10	-	**20**	10	10	40	**60**	10	10	40	**60**
Grid supporting (BESS)	-	20	-	**20**	400	410	145	**955** ↑	400	420	145	**965** ↑
Regional specific measures	-	-	-	-	-	-	-	-	-	-	-	-
Flex total	**(10)**	**39**	**99**	**128**	**408**	**459**	**331**	**1,198**	**424**	**469**	**331**	**1,224**
Flex excl BESS	**(10)**	**19**	**99**	**108**	**8**	**49**	**186**	**243**	**24**	**49**	**186**	**259**
Total Bess	**-**	**20**	**-**	**20**	**400**	**410**	**145**	**955**	**400**	**420**	**145**	**965**

Figure 5 - Flexibility measures presented as gross volume by TenneT

Source: TenneT

We think there is a possibility that this presentation may have caused unintended confusion in the message delivered (but we cannot say for certain). We mention in the recommendation that having an agreed set of KPIs that are standardised and repeatable between reports could help with understanding the messaging more clearly.

5.1.5. Which assumptions underlie the waterbed effect? How is this effect calculated in the model, and which factors ultimately determine the net effect of flexibility measures on specific bottlenecks?

In summary, the waterbed effect is a characteristic of meshed transmission network, underpinned by the network's topology and impedances; this is represented by the Power Transfer Distribution Factors (PTDFs), which is a standardised calculation function of the PowerFactory software. Please also refer to the answers to questions A1, A2 and A3 for more details and examples.

5.2. Natural Growth

Research Question 2

"In the second calculation round, Autonomous Growth was assumed (growth behind the meter at existing small consumers plus growth from new small-consumer connections, including residential construction). In the third calculation round, only growth behind the meter—"Natural Growth"—was included. The expectation was that the transition from Autonomous Growth to exclusively Natural Growth would lead to a clear reduction in the calculated overloads, because lower total demand growth was assumed. However, the outcomes of the third calculation round show that growth within existing connections accounts for a significantly larger share of the total increase in load than previously assumed. As a result, the capacity that was assumed to be available in the model from the reserved volume for new small-consumer connections now turns out to be required to accommodate Natural Growth."

5.2.1. Which assumptions and inputs underlie the determination of Natural Growth?

The forecast for Autonomous and Natural Growth comes mostly from the DSOs, as most of the load customers are connected at the distribution level. Some of the load (demand) forecast comes from TenneT, from their existing transmission-connected customers, these transmission-connected demand customers are forecasted as constant, unless specific information on future growth has been obtained by TenneT directly from the customer.

In terms of the DSOs demand, our research and technical sessions with the DSO stakeholders provided insight into the approach. The demand forecast is based on future energy scenarios, driven by carbon reduction and electrification targets. We found that between earlier grid congestion calculations (2024 and earlier) and more recent calculations (rounds 1, 2 and 3), the demand forecast has been revised to what is considered a more realistic level. A timeline is indicated below:

– Before round 1: Runs from 2024 and earlier contained initial, potentially high, targets for new housing connections and other decarbonisation assumptions. The revised assumptions of Fall 2024 were used as the demand forecast basis for round 1, in September 2025.

– Between round 1 and round 2 (i.e., between September and October 2025), there was a revision of the number of new connections from households.

– Between round 2 and round 3, there was a shift from Autonomous Growth to Natural Growth, as discussed in section 4.1, lowering the demand assumptions by only including demand for existing connections within their existing connection capacity and existing connection offers, and removing reservations for new connections for small consumers..

– After round 3: A future development expected for Summer 2026, to account for an expected transition scenario, as explained below.

In terms of actual vs. forecast demand, DSOs report seeing a decrease in total actual annual energy demand, probably driven by a combination of energy efficiency measures, and higher energy prices. However, for the peak demand (which drives system planning decisions), the trend is for an increase, potentially driven by heat pumps and non-smart EV chargers putting upward pressure in the peak demand. We have been made aware of a decision to model the Natural Growth by adapting the modelling to an expected transition scenario (VT for verwachte transitie). This modelling would continue to take into account the actual demand (metered), as in the current approach, with the difference being the assumptions on the number of installed heat pumps, EV chargers, etc in the forecast. Our understanding is that the VT scenario will mostly be based on actual realisations and less on required growth to meet 2050 targets. We understand that this methodology is being developed at the time of publication and expected to be available for modelling in Summer 2026.

In summary, the assumptions and inputs that underly the determination of Natural Growth are driven by the DSOs' best view of a realistic scenario for demand growth for existing connections and new connections that already have a connection offer. These assumptions were last updated for round 3 of the congestion calculations.

5.3. Modelling of grid-supporting battery systems

Research Question 3

"In the second calculation round, no grid-supporting battery systems were included. At that time, the calculation model proved unsuitable for this purpose: when TenneT attempted to model grid-supporting storage, the bottlenecks in the outcomes actually increased. The model was subsequently adjusted. In the third calculation round, approximately 1 GW of additional large-scale grid-supporting battery systems was modelled. The results now show that batteries have a positive effect on reducing overloads at bottlenecks, but the effect appears to be limited."

5.3.1. Which changes were implemented between the second and third calculation rounds?

As discussed in section 4.3, a logical model for battery dispatch was developed and implemented between Round 2 and Round 3. The model assumes perfect foresight for battery discharge: so, for example, if the exceedance lasts 4 hours but the battery can only discharge 4 hours at full output, the output is reduced to better reduce the exceedance for the full duration – this approach is consistent with system planning practices. Crucially, the battery is assumed to operate fully under the control of the TSO, as opposed to market-based operation, which is not reflective of reality unless there are guaranteed ways for TenneT to control the battery – either contractually or operationally (we will discuss this with more detail in the recommendations).

5.3.2. How does the model account for batteries and their impact on grid capacity?

In calculation rounds 1 and 2, the batteries were assumed to be grid neutral. This means that their charging and discharging profiles were assumed to be zero, i.e. not making the congestion worse or better. In calculation round 3, a logical algorithm was implemented to model BESS providing full grid congestion relief. This means that the BESS would be dispatched to support the grid by reducing overloading. The modelling of BESS was implemented based on actual connection requests to the DSOs and TenneT for their power capacity and locations, whilst an assumption of 4-hour batteries was made to their energy capacity. Please also refer to the answers to questions C.1, A.1, A.2, and A.3 for more details.

5.3.3. Is market-based operation of battery systems (i.e., without direct control by the grid operator) also included in the calculations?

As mentioned above, market-based operation of battery systems is not included in any of the main reported calculations. However, it was noted that the so-called calculation round 2-a, which was not the main reported calculation for round 2, in our understanding, had included market-based operation of BESS. Please also refer to the answer for C.4 below for more details.

5.3.4. Does the model allow alternative scenarios, focused on batteries, to be assessed, for example with different assumptions about location, capacity, or control of the batteries?

We believe the model does allow for different battery locations, capacities, and we have seen this demonstrated on a live model. Note that, in TenneT's model the behaviour of the batteries is captured by a forecast of load and generation, which is then used as input for a full load flow calculation. This implies that the model can also handle alternative scenarios, provided that a load and generation profile for these scenarios is available. We understand that the key challenge is creating the appropriate load and generation profile, depending on the modelling goal. Once this is obtained, the network model follows the principles as described.

With regards to control of the batteries, as mentioned before, TenneT assumed batteries were fully controlled by the TSO at times of grid constraints, and that they would operate fully with the purpose of alleviating grid constraints. TenneT did model batteries charging and discharging in accordance with the wholesale market - i.e., following price arbitrage opportunities using day-ahead prices and the modelling tool Plexos. For this modelling approach, they observed that the batteries would at times make exceedances worse in the modelling, due to price signals sometimes incentivising batteries to charge at times of network peak. This was the so-called calculation round 2-a, which was not the main reported scenario for round 2, in our understanding, but scenarios 2-b and 2-c which had batteries modelled as zero profile (grid neutral). Reported outcomes in October 2025 were based on calculation round 2-c.

5.4. Bottlenecks in line connections versus substations

Research Question 4

"Overloads can occur both at high-voltage substations and in the line connections between them. TenneT initially assumed that bottlenecks in the line connections would decrease once the substations were relieved by the FGU package of measures. However, the new model outcomes show that this effect is disappointing and that bottlenecks in the line connections are larger than those at the substations."

5.4.1. How does the model predict and what metrics/approach does TenneT use to evaluate the relationship between bottlenecks at coupling stations and in the line connections?

The grid model in PowerFactory that TenneT uses consists of network data, incorporating all assets of the transmission network. The impedances for all circuits in this data are set according to the monitoring and measurements from operational data, whereas the asset ratings are set to the values provided by the Department of Asset management within TenneT – as discussed in section 4.1, an input change in the modelling was to assume increased asset ratings (the MaxLimit program). The model also includes future grid expansions that are in a pre-design phase, and expansions that are expected to be realised. The impedances of future circuits are set according to calculated values, depending on the conductor type, cross section area, length of the circuit and other operational model.

The overloads (bottlenecks) are a function of the resulting power flows from the model runs when comparing them with the ratings of the assets and lines. The rated capacity of a line is different from that of the substation it connects to, therefore the percentage overload would look different, including showing higher overload in the line than in the substation (if the rating of this line is lower than the substation).

Another reason for observing changes in the overload of lines is power redistribution between different assumptions of the model. For example, if the power going into one substation is reduced, this power would go elsewhere in the meshed network and may show an overload in a line elsewhere.

5.4.2. What are the causes in the model (or explained by TenneT's experts) why bottlenecks in the line connections remain so prominent, despite bottlenecks at the stations decreasing?

We did not observe a counterintuitive movement of overloads between substations and lines during the model demonstrations with TenneT. The technical model has been capturing line overloading consistently throughout the calculation rounds. Therefore, there is no change to the technical modelling approach on assessing overload of line connections and substations. Please also refer to the answer to question D.1 above for an explanation about the comparative magnitude of overloads (in percentage, %) in the lines vs. substations.

5.5. Sensitivity, bandwidths, safety margins and assumptions

Research Question 5

"Since the start of the FGU approach and the first calculation round, TenneT, together with KGG (now EZK) and other partners, has refined the forecasts for demand growth (such as numbers of heat pumps and charging points). On that basis, a significantly lower demand development is now assumed than in the original calculations. Recalibrating these demand forecasts falls outside the scope of this assignment. However, questions remain regarding the suitability of the inputs and assumptions used in the models."

5.5.1. What are the input assumptions used and quality controlled by TenneT's? Have there been any clear changes of input assumptions between the penultimate and the last round?

We explored the quality control processes at the Focus Group meeting as well as the bilateral meetings with the DSOs and TenneT. Most of the demand forecast data comes from the DSOs. The main change of input assumptions is that: Autonomous Growth was modelled in the penultimate round whereas Natural Growth was modelled in the last round. Please also refer to answers under section 5.2 for more details.

There is a 2-stage approach to quality assurance in this process. First, each DSO undertakes quality control steps before making the demand information available to TenneT, following steps such as data checks and sense checks with any data deviations that are unexpected. Then, TenneT performs an additional quality assurance by looking at the data and identifying any outliers or unexpected variations that need to be investigated or explained.

5.5.2. Which assumptions underpin the model results, what are they based on, and how have they been translated into model parameters?

In relation to demand forecast, the assumptions are based on future energy scenarios, decarbonisation and electrification targets, and observed demand. The demand forecasts were created by the DSOs either for the Autonomous Growth modelled in Round 2, and the Natural Growth in Round 3. These demand forecasts were provided to TenneT as hourly demand profiles in standardised templates. The flexibility provisions implemented in the DSOs' networks were modelled by the DSOs based on overloading conditions provided by TenneT. The flexibility provisions would be represented by reduction in demand forecast profiles (i.e. incorporated into the hourly demand profiles), which were used as input into the model to calculate the net effect of the flexibility provisions. These hourly demand profiles were ingested by the model for the calculations. As mentioned in section 5.2, an improved demand forecasting approach has been identified by the DSOs and TenneT, named expected transition, which aims to reflect more closely actual observed demand, and to smooth the demand growth towards the 2050 targets, as opposed to implementing a steep growth to meet the targets.

In relation to BESS, the assumption of BESS fully controlled by TenneT was made in the third round of calculation, whilst BESS was profiled as zero in the main reported calculations in Rounds 1 and 2. The fully controlled BESS was modelled through a logic algorithm developed by TenneT together with Stedin. The BESS discharging and charging profiles were optimised based on overloading conditions and then inputted into the model as profiles to calculate the net effect of the BESS.

In relation to gas-fired power plants, they were modelled to support relieving grid congestion (they are contracted to TenneT to provide congestion relief services). Their generation profiles were created based on the congestion conditions, and the generation profiles were inputted into the model to calculated the net effect of the gas-fired power plants.

Please also refer to the answers to questions in sections 5.1, 5.2 and 5.3 for more details on the wider assumptions that underpin the model results and what they are based on in general.

5.5.3. Which sensitivity analyses have been carried out?

We do not believe that formal sensitivity analyses have been documented by TenneT or DSOs in their calculations. However, the modelling process does include sensitivity elements. The approach with different calculation rounds with the different demand forecasts and the different BESS-modelling approaches used can be seen as sensitivity analyses, i.e. varying specific input to the model to test and understand how the outcome (congestion situations) would be affected. It is noted that this has not been explicitly documented or communicated as sensitivity analysis. In the live demos, we observed sensitivity testing of different flexibility quantify related to the waterbed effect for different injection locations (see Figure 4 earlier), as well as the change in load flows in circuits when the tap positions of the Phase Shifting Transformers were varied.

ARUP

Appendices

Appendix A
Stakeholder Engagement

Appendix A
Stakeholder Engagement

Table 4 provides a list of the stakeholder engagement meetings Arup has conducted during the independent review process.

Table 4 List of Stakeholder Engagement Meetings

Meeting Date	Meeting Name	Attending Organisations
2026-02-26	Arup-EZK-TenneT Initial Introduction Meeting	Arup, EZK, TenneT (TSO)
2026-02-27	Arup-ACM Meeting	Arup, ACM (the regulator)
2026-02-27	Arup-Alliander Meeting	Arup, Alliander (DSO)
2026-03-02	Arup-TenneT Kick-off and Technical Meeting	Arup, TenneT
2026-03-02	Arup-TenneT RfI Discussion Meeting	Arup, TenneT
2026-03-02	Arup-Stedin Meeting	Arup, Stedin (DSO)
2026-03-04	Arup-TenneT In-person Technical Workshop	Arup, TenneT
2026-03-05	Arup-Enexis Meeting	Arup, Enexis (DSO)
2026-03-10	Focus Group Meeting	Arup, EZK, TenneT, Alliander, Stedin, Enexis, TU Delft
2026-03-11	Arup-TenneT Second Remote Modelling Meeting	Arup, TenneT
2026-03-11	Arup-TenneT System Operator Meeting	Arup, TenneT

ARUP

Client
Ministerie van Economische Zaken en Klimaat

Client reference
IUC-kenmerk 202602050

Author
Arup B.V.

Author reference
315432-00

Date
10 April 2025

Status
Final report

Disclaimer
This report has been prepared in accordance with the specific instructions and requirements of the client. Use of (parts of) this report by third parties, such as (but not limited to) disclosure, reproduction and distribution, is prohibited. Arup accepts no liability whatsoever towards third parties for the content of the report, nor may any third party derive any rights from the content of the report.

Arup B.V.
Beta Building, Naritaweg 118
1043 CA Amsterdam
Netherlands

arup.com