Network Topology Optimisation

NESO
National Energy
System Operator

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NESO: National Energy System Operator
EPRI: Electrical Power Research Institute
ICL: Imperial College London

Executive Summary

The network topology of the transmission network plays an important role in directing power flows across a congested transmission network. Identifying the optimal topology configuration has a direct positive impact on operating balancing costs. There have been various attempts by Transmission System Operators (TSOs) across the globe to develop automated Network Topology Optimisation (NTO) tools. Developments in new technologies, specifically GPUs and advanced data science, provide the opportunity to automate NTO across a TSO's operational business functions. However, the maturity of this technology for NTO remains at an early stage, with different TSOs and vendors conducting trials and deployments for control room support.

Our investigation demonstrated that NTO solutions are partially developed and operational across 13 TSOs in Europe, Asia and the USA, with up to $100m in cost reductions evidenced, based on the utilisation of basic NTO solutions deployed for control room support. We estimate that investment towards full automation in this area is likely to require between £50–100m over multiple years, with the benefits of full NTO Business as Usual (BaU) solutions exceeding the cost reductions evidenced to date. Operational planning at intra- and inter-day timescales is the dominant development area for these solutions and mostly requires a manual transition from a control room support team to run the simulations and advise operators. Scaled BaU implementation remains a key challenge, as the design of a pragmatic NTO algorithm must be embedded and synchronised within a TSO's digital estate.

The investigation indicates that no NTO solution yet addresses thermal, voltage, and stability constraints automatically, accurately, and at scale across multiple scenarios. The key findings of this benchmarking report, based on five technical comparative categories, are given below:

- **Topology:** There is no dominant mathematical routine in NTO. A handful of TSOs are in early, promising stages of implementing machine learning.
- **Power Flow:** All vendors studied had an approach to optimising congestion. DC solvers with AC post-validation is a mature method and universally available for implementation to alleviate thermal constraints.
- **Computation:** Use of GPUs are limited within NTO solvers. Underutilisation of available CPU resources was observed.
- **UI & UX:** User interfaces are underdeveloped for control room applications.
- **Implementation:** NTO solutions developed are not integrated with TSO's digital estate such as EMS (Energy Management System) and SCADA (Supervisory Control and Data Acquisition).

This project's analysis shows that, while NTO trials are promising, current solutions remain confined to test environments or limited control room support. The implications of a consistent data model and existing data management must be considered when packaging an NTO solution. The NTO solution is expected to work alongside existing planning and operational tools.

DC power flow solutions are computationally sufficient for optimising thermal congestion. However, existing NTO, and particularly AC Power Flow, algorithm speeds remain inadequate for intra- and inter-day timescales. Existing solutions also feature minimal UI and UX, rendering them less effective for control room use. A clear gap remains in Information Technology (IT) and Operational Technology (OT) integration, where aligning transmission network models is critical for scalable deployment and consistent results across control room decision support tools.

The Structure of the Following Report

The scope of this project was to understand the relative maturity of NTO worldwide, assess its suitability for the GB and NESO context, and provide recommendations on the structuring deployment. This work produced four outcomes:

- **WP1:** literature review to crystalise a technical definition of NTO
- **WP2:** assessed NESOs NTO capabilities, and interviewed vendors and TSOs
- **WP3:** performed a gap analysis, delineated across five solution areas
- **WP4:** generated a solution implementation plan and next steps

We interviewed six leading NTO vendors and nine TSOs across Europe, USA, Asia, and Australia. We further supplemented our analysis with desktop research on a more extensive group of global TSOs. We captured current developments and future plans surrounding NTO solutions.

WP1: Literature Review and Benchmarking

Section 1: Introduction to NTO

In 2023/24, GB transmission system balancing costs totalled £2,506m.[1] These costs are projected to increase significantly by 2030. Efficient configuration of transmission network assets to manage thermal, voltage, and stability constraints is a regularly used method to help minimise these costs.

NESO can mitigate operational costs by simulating combinations of non-generation-based adjustments and then carrying out those that are calculated to best improve overall power flows. Through the strategic reconfiguration of transmission assets, operators are able to alleviate congestion and minimise dependence on balancing services, a process commonly referred to as Network Topology Optimization (NTO). This is where NTO comes in as a natural next step, building off the strength of current practices. Today, constraint scenarios are identified, and then assessment comes both from operator knowhow and a variety of manual calculation tools in order to identify single transmission switches and limited topology controls for use in planning and real-time phases.

As supply shifts to more intermittent sources located at a distance from demand centres, there is evidence that assessing more constraint scenarios will become critical to unlock additional value for the end consumer.

Most TSOs today rely on human expertise, basic in-house modelling tools, and sporadic network data to improve power flow profiles across their network. Manual control methods simply cannot process thousands of network nodes several times a day, leaving significant value unrealised and exposing networks to inefficient operational schemes, resulting in millions of pounds in lost opportunity that consumers see reflected in their electricity bills.

NTO: A Dual Computational Problem, Qualified by an Objective

NTO is where an automated mathematical solver locates the best candidate topologies for improving overall power flows in the transmission network, following an objective.

The Objective—such as maintaining safe operating limits or minimizing operational costs—determines how both topology evaluation and power flow calculations are structured. These components form the basis of the NTO computational process.

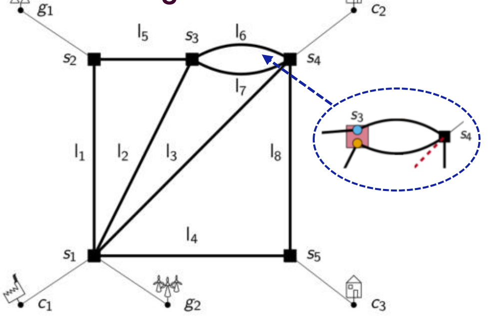
Why NTO can be Formulated as a Dual Problem, Increasing Pragmatism: In electrical transmission, a topology is a configuration of network elements at a specific point in time. These configurations are represented as topology actions (TAs), which are discrete variables (e.g., on/off; set point A/B/C). In contrast, simulating the flow of power across topologies involves assigning values to unknown continuous variables in order to meet safe network conditions. Calculating discrete and continuous variables involve highly distinct mathematical methods that constitute separate choices for NESO. We recognise that TAs and power flow can be co-optimised in a single mathematical formulation, using Mixed Integer Programmes (MIP). However, MIP ultimately accommodates the continuous and discrete variable types seen in NTO, only in a manner that increases computational intensity. Modern developments in solutions have focused on dual formulations of TA and power flow as enables more scalability, customisation and streamlining of methods. For this reason, power flow and topology evaluation are explored separately in WP1 section 2. The objective, topology evaluation, and power flow together comprise the NTO solver, which is a complete computational framework for determining optimal topologies.

Modelling: While topology evaluation and power flow are computed separately, they can be visualised together in a network graph model like fig. 1,[2] containing a minimum of $\boldsymbol{g}$, $\boldsymbol{c}$, and a TA.

- Generators (g)
- Customer loads (C)
- Allowed TAs must be defined by NTO developers. In fig. 1 these are:
  - Line switches (l), that turn off or on the cables connecting substations
  - Substation nodes (S), that contain busbars that can separate connections among g, C, and l elements

In the scenario circled in blue, $l3$ is switched off. At $S3$, a TA (busbar split) then reintroduces an indirect link between $S4$ and $S1$.

Figure 1.



Power flow is then modelled across this topology, solving for continuous variables such as active power (for DC and AC) reactive power and voltage, (for AC), and dispatch (for optimal power flow [**OPF**]), all in the context of the chosen objective.

Why NTO Matters: New Operational Complexities and Remedial Action

The UK's ambitious net zero targets have significantly reshaped the electricity grid. In 2024, clean generation accounted for 56% of GB's electricity[3]—a major energy transition milestone. Unlike fossil fuels, outputs from renewable sources such as wind are inherently variable. As a result, the frequency of over- and under-generation has risen substantially. In parallel, national demand for electricity is forecast to double by 2050 due to the electrification of heat and transport, and the rapid expansion of AI-powering data centres.[4]

In GB, this variability is further complicated by geographic factors. Most wind farms are located offshore in the north, while areas of demand are concentrated in the south. GB's corridor-shaped landmass limits the number of alternative transmission routes available to redistribute power efficiently. As a result, these structural constraints contribute to transmission bottlenecks that place recurring pressure on infrastructure.

Structural reinforcements and new capital projects that increase grid capacity are not only costly but take years to carry out. Renewables, reinforcement challenges, and the difficulty of storing electricity, are challenges that all transmission operators are facing across the globe.

Our Ambition and Objectives: Why NESO is Undertaking this Research

NESO aims to deepen its NTO capabilities to empower responsive network management and enhance network efficiency. The current manual process is FTE-intensive and involves numerous tasks, such as forecasting, data preparation, model conversion, feasibility evaluation, implementation, and revalidations. NESO's research is focused on identifying fit-for-purpose solutions that leverage state-of-the-art techniques and orchestrated computation, seamlessly integrate with existing operational technology stacks, and make full use of available data sets.

NESO is committed to working collaboratively and joining forces with key players in the industry to accelerate the adoption of innovative NTO solutions. Despite past challenges, NESO recognises that partnership and shared expertise will be crucial in overcoming these barriers and driving forward progress in network optimisation.

Methodology and Approach

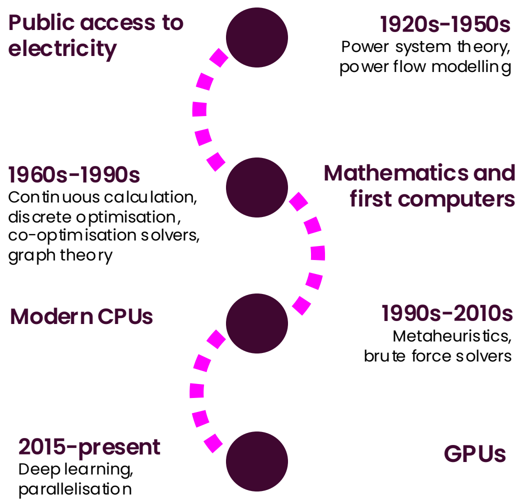
This report draws upon an extensive research approach encompassing three key strands: a detailed analysis of global academic literature on NTO, a review of best practices within the transmission sector, and a benchmarking exercise comparing NESO's NTO practices against industry standards. The following sections provide an overview of each strand, offering both theoretical insights and practical perspectives that inform the study's findings.

NTO Research geography

Section 2: A Review of Research and Methods

Trends in the Research Landscape

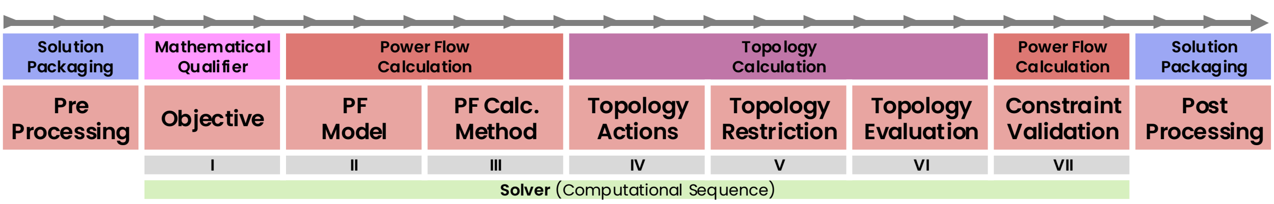
NTO represents the confluence of several longstanding and distinct academic areas. These areas became established over time alongside specific breakthroughs. Line switching was first Topology Action (TA) identified as a means of power systems control in 1985.[5] 2008-10 generated the modern attention the field has held until today, when commercial solvers first performed full-scale NTO through the use of Mixed Integer Programming (MIP) methods.[6,7,8] In the last five years, the discipline has shifted from theoretical dispatch optimisation, to network constrained optimisation, driven by the sponsored research and operational demands of European TSOs.[2,9,10,11] This new loose body of literature that has directly developed solvers is at the frontier: benchmarking methods and exploring strategies that reduce computational complexity. Research teams have seen a make-up from the following scientific domains:



- **Power systems engineers:** Understand requirements, grid context and electrical theory
- **Mathematicians:** Integrate optimisation methods and explore simplification
- **Computer scientists**: Encode mathematics, explore AI/ML techniques, maximise hardware

Identified "Steps" of a Solution

Based on our review, we identified that an NTO solution always involves weaving together and developing the steps in the below diagram. Steps can be thought of in a rough sequence that orchestrates all necessary data to generate optimal topologies.



The seven stages of NTO solver computational sequence are explained in the next subsections.

I. Objective

All solutions should first consider the goal of the optimisation. One primary objective can be selected, or a secondary objective can combine with a primary objective. The latter is a multi-objective function—a category that can also be made up of two primary objectives.

Objective				
Primary: (minimise)			Secondary: (optimise)	
Thermal (P) congestion[12,13]	Voltage (Q, V) violations[14]	Total system cost[6,15]	Fewer TAs[16]	TAs across timestamps[17]
		Multi-objective-function (e.g.)		

The chosen objective restructures the objective function—the complete algebraic formula of

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the solver that scores the effectiveness of a single topology. Multi-objective functions involves agency in assigning weights or penalties to each objective, subjective to relative importance.

II. Power Flow Model

Power Flow (PF) models how electricity moves through networks. DC PF uses linear equations and calculates active power (P). AC PF further calculates reactive power (Q) and voltage (V), introducing sinusoidal nonlinearity. Real worldwide transmission is done with AC, meaning DC PF gives an approximation of Q, and V, typically within ~1-2% accuracy of AC PF,[18] with error limits of up to ~25%. In NTO, PF is typically calculated with fixed generation and demand data, as unforeseen balances materialise in the day-ahead, which the control room must remedy.

III. Power Flow Calculation Methods

PF calculates feasible continuous variables P, Q, V. Optimal PF (OPF) further calculates generation based on an objective. With nonlinear treatments on CPUs for each, AC PF is 18x slower to solve than DC PF for a NESO-sized network.[19] Linear DC PF on GPUs is many magnitudes faster still.

	Power Flow Model	Continuous Variable Calculation	
		Linear treatment	Nonlinear treatment
Method	DC PF	• Linear Prog. • Quadratic Prog.	• Gradient Method
Calc.		• rapid • GPU-suited	• slow • CPU-suited
Method	AC PF	• Linearisations • Relaxations	• Newton Raphson • Fast Decoupled LF
Calc.		• slow & approx. • GPU-potential	• very slow & exact • fully accurate

IV.*a.* Topology Actions (TAs)

Candidate topologies are defined by the allowed TAs—i.e. adjustments to component settings.

	Topology Action	Power Flow		Explanation
		DC	AC	
Binary	Line switch	✓	✓	Connecting or disconnecting a single transmission line.
	Busbar split[15]	✓	✓	Splitting a bus into 2+ sections, redistributing component connections.
	Busbar assignment[13]	✓	✓	Shifts one or more components to a different substation busbar.
Discrete	PST set point[20]	✗	✓	Phase Shift Transformer. Adjust V mag & ang, redistributing P and Q flows.
	HVDC set point	✗	✓	Used to schedule large P transfers across distant regions.
	Other Q/V moderators	✗	✓	Capacitors, inductors, STATCOMs directly inject or absorb Q, stabilising V.

IV.*b.* The Varying Impact of TAs

A solver can search for the optimum solution among simultaneous TAs, which when increased see exponentially diminishing returns on the objective function and exponentially increasing computational costs. Optimal sets of TAs must be executed together, as executing only some has no relationship with the objective function.[6]

V. & VI. Topology Restriction and Optimisation Methods

To simplify computation developers can reduce the allowed TAs, maximum number of simultaneous TAs, and unimpactful TAs being assessed. For the latter, sensitivity factor models are used.[21] As optimisation methods, enumerative solvers calculate the Power flow for all topologies that remain unrestricted, or alternatively, co-optimisation methods (e.g. MIP) calculate the joint TA and PF decision space to reach the global optimum.[22]

VII. Constraint Validation

Constraints are boundaries that PF must meet to ensure safety at the component- and network-level, and are typically validated post-optimisation to reduce multi-objectivity. Integrating validations is key to reducing manual operator effort, who otherwise use separate tools. See appendix table A1 (p24).

Modern "Augmentation" Methods – An Analysis of Pros and Cons

Modern methods do not replace the mathematical base of NTO but instead harness and accelerates it. The principles of TA and PF unification remain; however modern methods go further to augment the search or calculation process. Three leading categories of modern method have been identified in this report for NTO.

Metaheuristics

Augments by sampling the search space intelligently rather than exhaustively; a net is cast by many concurrent "individual" calculations with diverse variable values.[23,24,13] During a calculation loop, individuals reach an objective function value and performant individuals are recorded. After each loop, each individual's variables are tuned based on the metaheuristic's strategy, iterating towards the optimum over many loops.

- A global search capability that reliably approaches the optimum.
- Robust at solving for noisy multidimensionality. Excel at, and accommodate to, nonlinear problems.
- Demanding computations when many individuals loop high-node networks; costly to time + hardware.
- Scales well to complexity: via GPU parallelism and eliminating gradient data stored in RAM.
- Parameter values must be chosen, which can affect performance dramatically.
- Optimal results can vary between simulations due to the stochasticity that all strategies introduce.

Reinforcement Learning (RL)

Augments by learning optimal actions through trial and error, leading to rapid prediction that replaces calculation.[25] RL involves an agent in an environment. For NTO, the environment presents historical loads and injections, asking the agent to make decisions to select among variable values.[2] The decision policy may have stochasticity, and it factors into the agent's future decisions the magnitude of rewards or penalties received across attempts.

Graph Neural Networks (GNNs)

Augments by representing topologies as graphs, leveraging lessons from neurochemical networks to internally model power flow.[26,27,17] GNN layers propagate information between connected components, an operation that is conceptually similar to electrical activity in a grid. Once trained from the outputs of classical optimisation methods, they can predict effective topologies without re-solving underlying equations.

Machine Learning (ML) Methods Under the Context of NTO

RL and GNNs are both Machine Learning methods. As a subfield, ML methods undergo a training phase, then enabling inference that reduces calculational burdens. ML methods share general upsides and downsides:

Artificial Intelligence (AI)
The multidisciplinary field of computer reasoning

Subfield →

Machine Learning (ML)
Predictions from ingested training data via models

Pros

- Can locate novel strategies[28]
- Has undergone clear benchmarking
- Scales effectively
- Lightning fast once trained[17]
- Open-source ecosystem
- Agile to real-time needs
- Tractable to AC PF[17]

Cons

- Human-in-the-loop still needed
- Involved training
- Accuracy ranges rise on unseen data[25]
- Requires cleansed historical data
- Fragile to network change
- Vulnerable to data perturbations
- Limited Interpretability
- Struggles with multi-objectives

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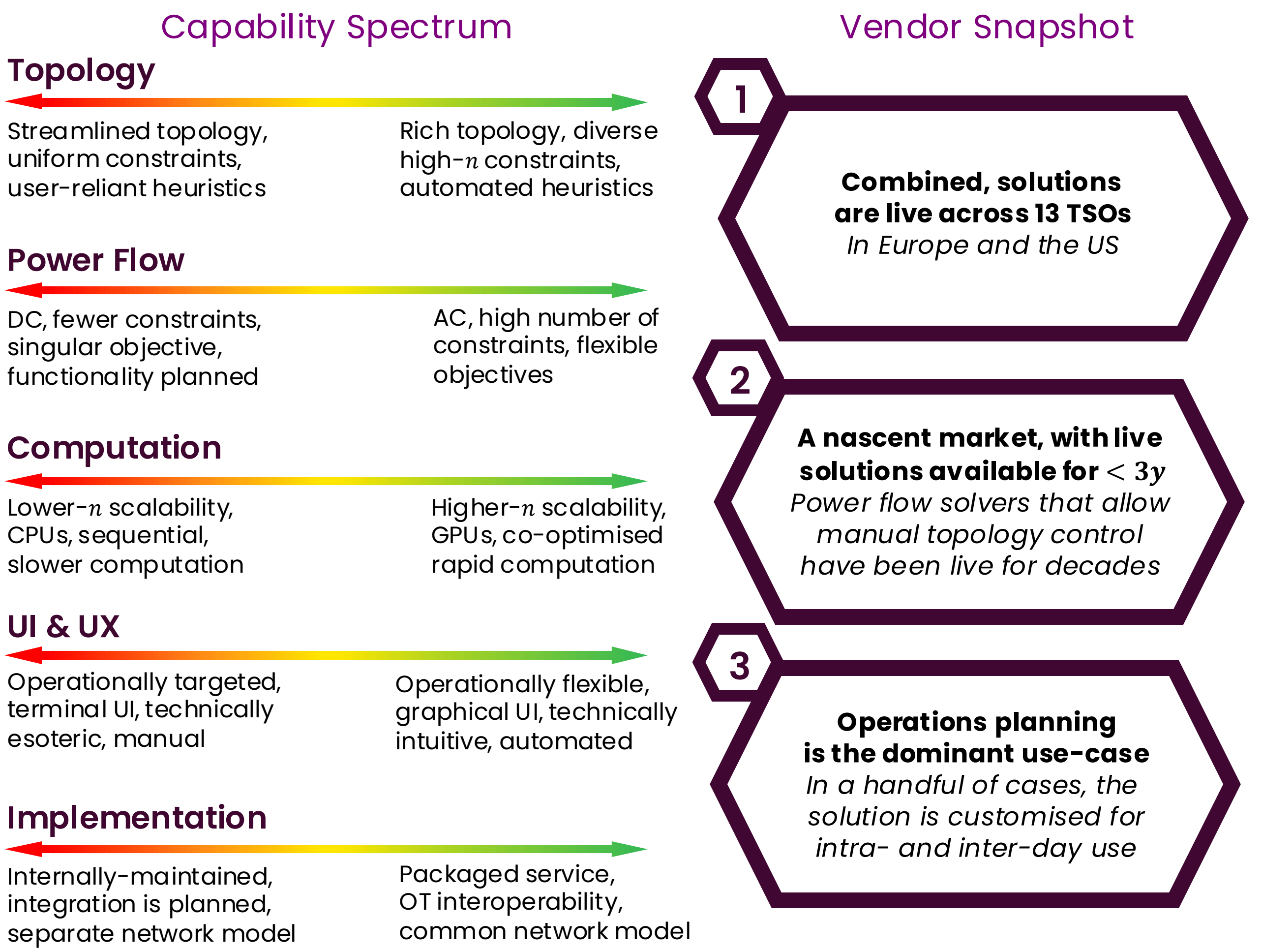
WP2: Current State Assessment

Section 1: Vendor Technology Analysis

We identified seven vendors who are working actively on NTO solution development, we successfully gained access to evaluating six of the vendors as part of this report. The work conducted here involved detailed interviews with six prominent vendors who have developed NTO solutions, each with specific capabilities driven by two main factors: their early adopter clients requiring constraint management tools for control room applications, and their historical optimisation suites such as generator cost scheduling and security-constrained power flow. In the past few years, vendors have acknowledged seeing a rising NTO demand amongst clients, and in most cases have reserved funding for further development.

We also engaged with the wider NTO solution and research community by attending the LF Energy Summit Europe 2025[29] and Topology Optimisation Symposium 2025.[30] Here we had the opportunity to walk the floor and speak to a wider group of vendors who have bespoke solutions in earlier stages of implementation.

Based on the information gathered from the vendor interview sessions, a spectrum of five categories was defined for assessing the maturity of NTO solutions, with a snapshot of the landscape represented below.



Section 2: Assessment of Each Technical Category for Vendors

Following vendor interviews, demos and discussions, we summarised the for each of the five technical categories:

Topology

There is no dominant method for defining network topology
Based on objectives, definitions vary from node-edge graph theory to numerical-based digital twins. On one hand vendor developers capture general TSO best-practices. On the other hand, some implement network-specific heuristics captured from experienced operator staff.

Power Flow

All vendors studied had an approach to optimising congestion
Solving for voltage constraints, network reliability and risk planning saw lesser deployment amongst TSOs.

Vendors are still moving towards AC linearisation
DC solvers with AC post-validation is a mature method and universally off-the-shelf.

PF and OPF are essential subroutines within solution objective function
Where control variables are adjusted to achieve the solution objective, mathematical formulation of OPF will be incorporated in the design.

Computation

Use of GPUs is limited
Despite GPUs being central to modern computational advancements (e.g. in GenAI and big data querying), their adoption is limited. The ability to rapidly solve complex NTO will depend on future GPU uptake

Simulation speed is sufficient for single objectives and DC
Factoring for large (6-digit bus) networks, with a high number of constraints, calculation can sit between 2-15 minutes.

UI & UX

Richer topology models tend towards visual and geospatial UIs
This grants operators full agency to manually explore topologies and customise processes, often at the cost of proscriptive simulations that solve for the optimum solution across the whole transmission network.

Solutions should be understood in terms of modules
Rather than black-boxes spanning the remit of control room objectives.

Deployments of UI are in early stage
Bespoke developments were seen for specific cases, such as line switching optimisation for thermal constraints

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Implementation

Service models vary, yet close collaboration drives advancement
There is a level of flexibility around the extent that management and maintenance responsibilities reside with the operator or the vendor.

The solution model's alignment to the real network is paramount
Especially for real-time and scaled usage.

Most vendors contend with the integration of EMS / SCADA
In the process, they spend effort separately replicating a network model.

Section 3: Best-in-Class Vendor NTO Solutions

Criteria	Definition of Best in Class
Topology	**Best-in-class detail of component definitions** Detailed types of TAs (or control variables) such as substation buses and couplers, line switches, PSTs, HVDCs, and P/Q moderators. Variable adjustments of TAs within the solver that optimise for both thermal congestion and voltage network constraints. **Best-in-class solving of global optimal topology** Employs a simple node and edge network model to brute force assess a majority of the search space to identify optimal topologies.
Power Flow	**Best-in-class solving of AC and power flow equations** Flexible objectives and TSO control limits that define an integrated PF subroutine that solves every defined candidate TA set. Availability of an AC PF model with the Newton Raphson method in the direct solver, not only as a constraint validation.
Computation	**Best-in-class use of modern GPU parallelism** Fastest solution by significant margin uses GPUs to solve DC PF with a linear treatment at massive simultaneous scale. GPUs thrive on structured, repeatable computations and low VRAM. AC PF's branching logic and irregularity demands innovative, complex linearisation. Further, legacy CPU code bases must be refactored.
UI & UX	**Best-in-class automated operation with less human interventions** Automated execution for 95% of TAs, with use of operator-defined heuristics to optimise from a selection of highly robust TA sets. Used in intra-day as well as operational planning timeframes. Analytical options are provided for operators to select within the UI, including TA control variables choices and objective functions.
Implementation	**Best-in-class common network model** Orchestrated pre- and post-processing provides cohesion with OT estate and automates cleaning of some input data and output files. Model encoding that is modular and consistent across steps for seamless computation. Integrates constraint validations into solver.

Capabilities are fragmented—vendors are advancing along different frontiers of performance, but none have yet converged on a solution that delivers excellence across multiple categories or end-to-end. Some combine NTO and AC PF in a solver that optimises reactive power flows and voltage profiles. Others solve DC PF and validate with a full AC load flow. A few vendors utilise GPUs for parallel optimisation. Market solutions are primarily developed for operations planning, with limited automation or integration within EMS and SCADA.

Section 4: An Analysis of NTO among TSOs

The analysis of TSOs involved a comprehensive approach that included a detailed examination of various types of organisations, such as TSOs, Independent System Operators (ISOs), and other relevant stakeholders. The research covered a wide geographical range, including the UK, Europe, Asia, North America, and South America. Over 15 private and public organisations were included in the study, with sizes ranging from small regional operators to large national power system operators.

The analysis comprised two key strands: desktop research and interviews with TSOs. The desktop research involved a detailed review of publicly available information on NTO for those TSOs and adjacent subjects. Interviews and working sessions were conducted with selected TSOs to gather practical insights and validate assumptions. This approach ensured a thorough understanding of the current state and future potential of NTO solutions within the industry.

The TSO assessment criteria included several main topics, such as the general status of NTO, the business drivers behind NTO, deployment maturity, technological advancement of NTO solutions, cost and resource requirements, operator experience, and future ambitions.

TSO Assessment Criteria Spectrum

Deployment Maturity

Initial pilot projects or PoC stages, with limited operational integration.

Fully operational integration of NTO solutions, with continuous R&D

Advancement of NTO

Limited to topology control only, NTO methods in planning only, basic methods and models

Advanced methods and models integrated solvers, innovative use of compute hardware

Cost & Resource Requirements

Limited investment in NTO solutions, with minimal resources allocated.

Significant investment in NTO solutions, with robust training and support, strong industry collaboration

Operator Experience

Manual processes with limited operator support and minimal UX and UI

Empowered operators, modular systems and UI, introducing more automation

Future Ambitions

Limited or no strategic roadmap for NTO development

Comprehensive strategic roadmap, considering innovative techniques, strong partnerships with vendors, regulators, and academia

Section 5: TSO Assessment Summary

Deployment Maturity

Many TSOs are entering the pilot phase for new E2E NTO solutions

Completion of R&D: Many TSOs started with pilot projects to test NTO solutions in controlled environments.

Topology Control and Planning: All TSOs have procedures for corrective TAs or do manual NTO using unintegrated tools in long-term planning.

Advancement of NTO

There are several streams of advancement in IT and methods

Integrated Solvers: TSOs are recognising the value of orchestrated constraint validation.

GPUs: A handful of TSOs have seen real breakthroughs by using lightweight cores to rapidly brute force DC PF with linear treatments.

Deep Learning: Prohibitive nonlinear AC PF calculation times have shown to be surmountable by RL and GNNs, yet associated operations management and processes are in their infancy.

Fast Delivery with Vendor Service Models: Outsourcing time-intensive pre- and post-processing development to vendors has shown promise.

Cost & Resource Requirements

Implementation and delivery comes with identifiable investments

Hardware: Investment in high-performance computing infrastructure including GPUs and CPUs comes part-and-parcel with complex NTO.

Software and Licensing: Purchasing or licensing NTO software solutions from vendors involves covering costs for initial setup.

Engineering the Ecosystem: Harmonising a solution with the current tech estate and structuring model management increases timelines.

Training and Support: Providing training and support for operators to ensure smooth integration and positive user experiences.

Collaboration: Diverse internal teams, as well as vendors or research parties are brought together to combine expertise and inputs.

Operator Experience

Operator Experience varies significantly across organizations

Completeness: Solution models calculate with much less context than operators. Thoughtful adjustments can significantly bridge this gap.

UI & UX: With human-in-the-loop requirements, operators benefit from intuitive UIs that presents relevant and polished data.

AI in BaU: Contrary to assumptions, operators are not apprehensive to AI-based solutions if they aid taskwork.

Future Ambitions

Enhancing NTO for the energy transition and network resilience

NTO as a Strategic Priority: Many TSOs have identified NTO within organisational missions in response to an evolving power landscape.

Collaboration: There is a constructive openness among TSOs to share NTO learnings, open-source research and findings, and join initiatives.

Capability Roadmaps: Gap areas such as voltage violation solving and transient stability constraints are seeing further R&D investment.

Section 6: NTO Best Practices by TSOs

Nine TSO interviews, as well as desktop-based literature reviews, were conducted to gather insights into ongoing developments and upcoming strategies for NTO solution adoption. All TSOs interviewed expressed great need for an NTO tool which can support network access planning engineers as well as control room engineers with constraint management and network operations. Our interviews with two continents in particular can be elaborated on. In Europe and the US, development of NTO solutions has branched in different and directions with contrasting benefits and lessons, based on differing market circumstances. TSOs internal policies drive the development and implementation of NTO.

For Europe, the context of EU zonal market integration and a continent with many neighbouring tie lines has necessitated rapid intra-day optimisation. Here, TSOs have developed in-house solutions and collaborative initiatives.

In the US, ISOs and RTOs span multiple states and coordinate across vast geographies, giving them a unique vantage point for system-wide optimisation. This scale has led to the implementation of multi-purpose vendor solutions and scenario simulation and mitigation.

Criteria	Definition of Best Practice
Deployment Maturity	Begin with pilot projects to validate feasibility, progress to full operational integration for reliability, and maintain ongoing research and development to keep solutions at the cutting edge.
Advancement of NTO	Employ a modular and scalable technology stack, integrating advanced algorithms or deep learning, with seamless OT estate compatibility. Collaboration with vendors is common.
Cost & Resource Requirements	Customise investment in hardware, software, and human capital based on the need and encourage industry collaboration to share experiences and reduce sector-wide duplication of effort. In-house data scientists develop the solver, oversee model management.
Operator Experience	Empower operators with visual, geospatial interfaces and modular systems, allowing for manual exploration and control, while gradually introducing automated support as trust and familiarity grow. Pre-empt collaboration with the control room to gather requirements.
Future Ambitions	Develop a strategic roadmap for integrating NTO systems, nurture ongoing partnerships with vendors, regulators, and academia. Set NTO as a BaU tool.

WP3: Gap Analysis

Section 1: NTO Solution and Technology Gap

The literature review and technology analysis performed in this project indicate that no vendor or TSOs have an operationally mature NTO solution fully embedded into their wider IT and OT estate. Development of NTO decision support tool is in early stages. Below is a gap analysis performed on the five key NTO technology categories:

Topology
Graph-Based Optimisation Techniques: As a cornerstone of NTO, graph theory and not just PF must be engineered to manage thermal constraints and increasingly support voltage and dynamic stability. These methods simplify complex transmission networks by representing system components and control variables as nodes and edges. Future work should expand these techniques to include a wider range of simultaneous TAs such as busbar couplers, switches, reactive power devices, dynamic line ratings, VAR compensators, tripping schemes, and active network management. This will enhance system flexibility and improve optimisation across multiple constraint types.

Power Flow
DC Limitations: Most vendor and TSO-developed NTO tools rely on DC power flow or linearised AC formulations to manage thermal constraints. These approaches are computationally efficient and suitable for congestion management but fall short in accurately modelling voltage profiles, reactive power flows, and dynamic stability—especially as networks operate closer to their limits. DC and linearised AC methods assume voltage magnitudes remain near nominal values, leading to systematic misestimations in stressed conditions. Fast and full AC solvers, which are essential for capturing these complexities, have not been adequately integrated into existing decision support tools. **Gaps in Associated Constraint Integration:** Current DC-based optimisation tools are typically used by control support teams to advise control rooms, but they lack the capability to address voltage and dynamic stability constraints. Control variables are often limited to basic elements like busbar couplers and line switches, while critical devices such as quadrature boosters, static VAR compensators, capacitor banks, and dynamic line ratings are overlooked. Expanding NTO solutions to model both real and reactive power flows—and their interdependencies—is essential for addressing thermal, voltage, and dynamic stability constraints with sufficient accuracy.

Computation

CPU Refinement: Vendors and TSOs have primarily developed solvers for CPU-based environments. Tests on large-scale networks (e.g. >10,000 buses) reveal underutilisation of available CPU resources. To improve performance, future implementations should incorporate multi-threading, multi-processing, and full workload distribution across cores.

GPUs for AC PF: GPUs grant faster computational; speed leading to more TA sets to be optimised in less time. Future work should seek to solve AC PF with a linear treatment, or a partial linear-nonlinear treatment where GPUs and CPUs work in parallel.

Deep Learning for AC PF: More exploration would help determine whether deep learning has the potential to overcome prohibitively intensive nonlinear AC PF computation.

UI & UX

Vendors and TSOs have mainly focused on development of UI tools for control support applications. Full automated UI and UX deployments are in the early stages, and a wide gap has been observed for usability among control room operators.

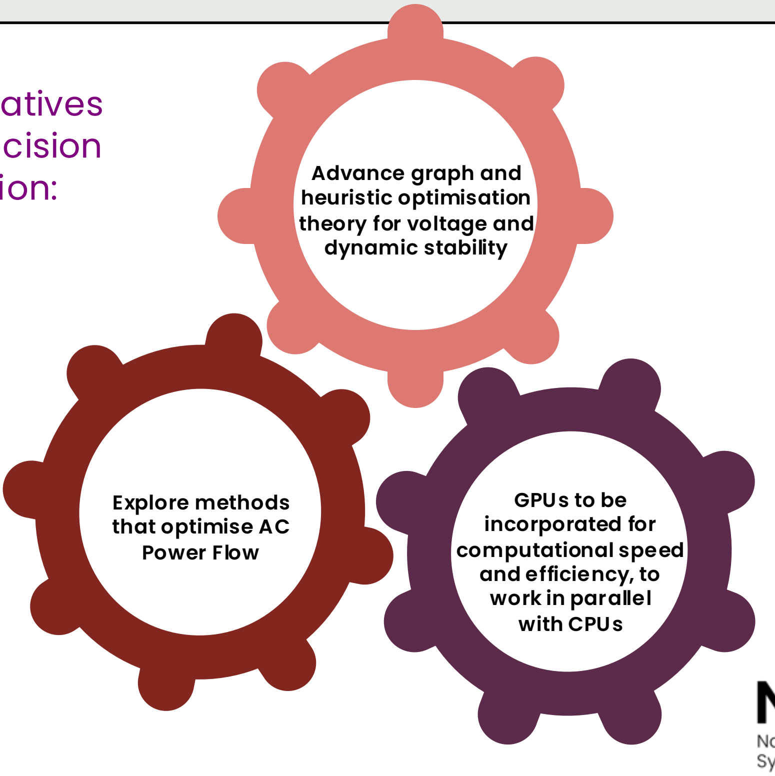
With human-in-the-loop continuing as the paradigm, NTO solvers must be made for operators, have auditability, and weigh-up considerations.

Implementation

Vendors and TSOs have not fully integrated NTO solutions into existing IT and OT platforms. Automated data orchestration are in the early stages.

There is a lack of model alignment between EMS, SCADA and the NTO solver, which is paramount for simulation integrity and efficiency within BaU deployment.

Design Imperatives for an NTO Decision Support Solution:



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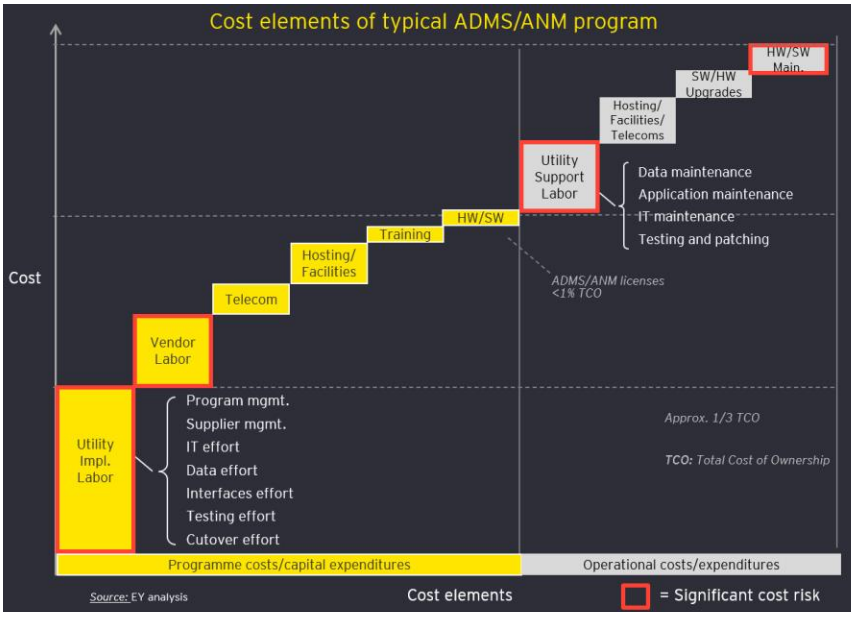
Section 2: Estimation of Cost

There is limited data available to directly indicate the cost of full or partial NTO solution. This section makes estimates based on similar technology deployments.

In terms of infrastructure, typical Advanced Distribution Management Systems (ADMS) or Active Network Management (ANM) systems are similar to NTO, involving network modelling, topology manipulation, constraint management, and data orchestration. National-scale implementations integrated across IT and OT estates have historically attracted investment levels of £10–15 million. Below outlines the typical cost structure associated with ADMS and ANM platforms.



- Approximately 70% of total cost of ownership (TCO) is related to implementation labour of ADMS or ANM
- Suites include load flow, and contingency analysis
- Internal labour spend as FTE ranges from 50-75% of programme costs
- Vendor licenses represent a fraction of CAPEX
- Vendor labour can be the largest part of their price

For NTO automation, existing off-the-shelf vendor services are estimated to cost between £1m and £5m per annum to provide DC PF-based optimisation of thermal constraints. It is anticipated that the cost of these services would rise as additional capability is developed by the vendor, such as AC PF-based optimisation of voltage or dynamic stability constraints.

Extending beyond existing capabilities will require research in key areas highlighted in our gap analysis (p16-17). The time to bring this research to market will vary depending on the annual investment.

Research Investment (per annum)*	Estimated Time to Market (years)
£0.5m - £1m	15 - 20
£1m - £5m	10 - 15
>£5m	5 - 10

* The research investment estimation is validated with similar projects such as Power Potential which was a joint NESO and UK Power Networks project for proof-of-concept development of a Distributed Energy Resource Management System (i.e. also known as ANM) which optimised use of Distributed Energy Resources (DERs) reactive power for addressing transmission network voltage constraints in the South Coast of the UK. The project duration was 3 years and costed a total of £10m between 2019-2021.

Section 3: Estimation of Value

Estimating the value of NTO automation is complex as there are a number of factors that determine what can be achieved by a TSO, including:

- Existing level of NTO performed manually
- Operators risk management policies
- Market design

If these factors are ignored, studies indicate large estimated cost savings. Studies by European Universities indicate potential for up to 50% reduction in constraint costs with computationally intensive NTO solvers. However, these require long simulation times and large volumes of simultaneous TAs that are impractical for a control room operator to execute..

Topology control, where one—or in rare cases two—pre-identified TAs (typically binary) are executed to implement a corrective action in the system, has been a longstanding manual practice in NESO and among TSOs internationally. Manual methods become more complex when two or three TAs start to be considered, and it is estimated that this number of TAs alone could add a further 1–3% of savings, complex NTO aside. For NESO, this can be equivalent to £75m per year in cost reduction when considered against current balancing costs.

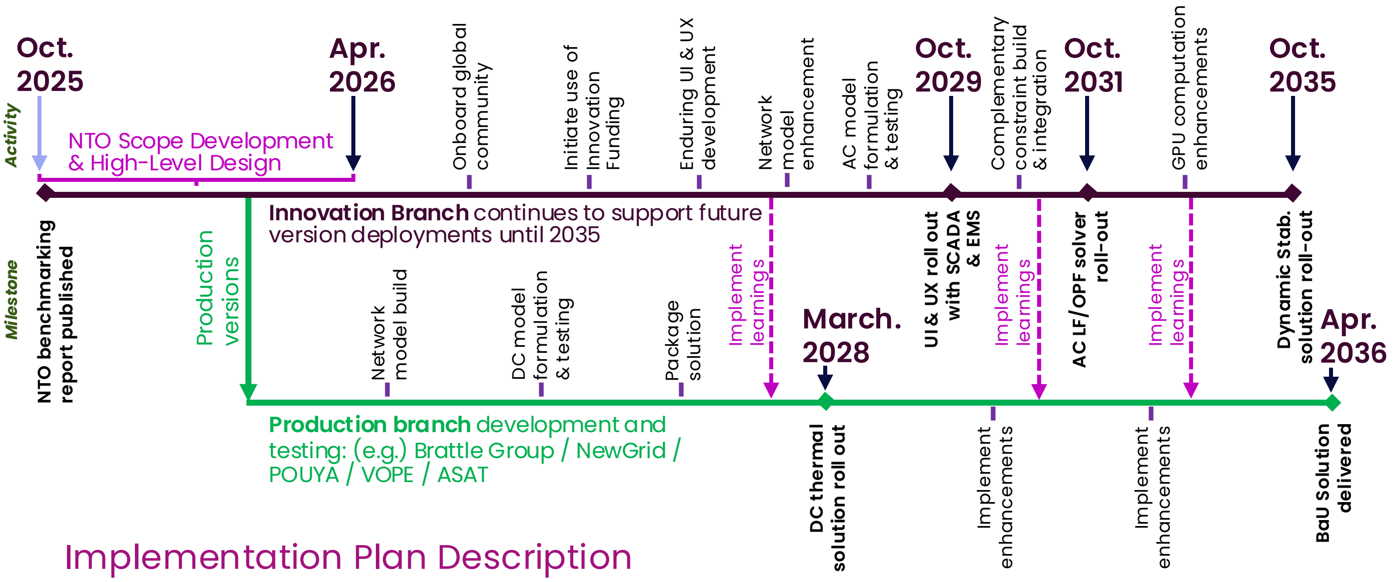
In practical examples that confirm this estimation, in North America there is evidence of a vendor supplied NTO decision support tool for thermal congestion management that has saved $100m from congestion cost incurred while increasing reliability and minimising renewable curtailment impacts.

If deployed in planning timescales, NTO could also increase the number of scenarios that an operator could review. This has potential to improve the planning process, leading to topology efficiency when taking complex outage plan combinations. This may offer further cost reductions for the end consumer.

The nine TSOs interviewed in this project all see NTO as a lever to reduce costs from grid congestion, with the impact varying dependent on market design. In addition to balancing cost savings, there is also an understanding that NTO can provide a more rapid assessment of topology following a transmission system fault and can assist an operator to return the transmission system to its desired state. This adds risk management value to a TSO.

WP4: Implementation Plan

NTO as a decision support tool will be an essential and daily part of power system operations, part-and-parcel of the management of a large-scale network with complex thermal, voltage and dynamic stability constraints. It is recommended that NESO incorporates an implementation plan with the formation of a global community. NESO should support the wider industry with providing the NTO solution across a 10-year timescale. The recommended high-level NTO Implementation Plan is demonstrated below:



Implementation Plan Description

NTO is not a commercial off-the-shelf product meaning NTO cannot have a ‘plug-in’ implementation. Rather, solutions require a level of customisation to cater individual TSO business practices, but the core solution features can be shared across multiple TSOs. solution development should target NESO’s priorities in a phased deployment, which can develop at minimum:

- **Topology:** An advanced graph heuristic model that contains multiple, detailed TA types that can simulate key constraints.
- **Power Flow:** Use of full AC load flow models to calculation of reactive power flows and voltage profiles.
- **Computation:** Fast calculation of multiple constraints, cardinal points, and timescales through use of a complete network model.
- **UI/UX:** Control room approved UI and solver support embedded in BaU processes.
- **Implementation:** Solution is cohesive with OT and IT estate, fully automating a data pipeline for input and output.

The NTO solution will address constraints observed during intra-day operations, with the same features also being applicable within operational planning.

The Implementation Plan consist of a Production Branch and an Innovation Branch. For the Production Branch, we expect an MVP solution with the following features by March 2028:

- DC optimisation of topology for thermal constraints at the full-GB network level.
- A workable UI for operation at feasible near-term timescales, with a dedicated support team that supports application in the control room.

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The Production Branch is recommended to roll out further enhanced versions between March 2028 and April 2036, where learnings have been transferred across from the Innovation Branch to enable control room with more advanced NTO features.

The Innovation Branch is recommended to target the development of three advanced NTO features:

- Enduring UI and UX visualisation integrate SCADA and EMS
- An AC PF and OPF solver
- A Dynamic stability assessment module

The Innovation Branch is recommended to operate over a 10-year period beginning in April 2026. During this time, it is advised to establish a consortium comprising of academic institutions, vendor(s), and professional organizations to collaborate jointly with developing a comprehensive NTO solution. It is recommended that insights and findings from the Innovation Branch should be continuously integrated into the Production Branch, where additional NTO features can be progressively deployed across control room and planning departments. It is advisable to engage with other TSOs to leverage their experience and test their existing NTO solutions within the NESO environment.

NTO goes far beyond system design and implementation. It requires reimagining control room processes to standardise and optimise control room operations. It is recommended to appoint an expert team that understands the linkage between technology and business will add significant value. Designing an NTO solution requires a multidisciplinary team with expertise in power systems, data engineering, network modelling, data science, and programme management. This will ensure a technically skilled team can manage and coordinate the implementation end-to-end, and that relevant departments within NESO & wider global community are active participants.

It is recommended that advanced areas such as fast AC PF, deep learning, and sequential solvers should be explored separately through a dedicated research branch. Stakeholder engagement is an essential stream within BaU implementation, such as regulating the number of TAs that can occur pre-fault or following a component failure.

Implementing the NTO programme over a 10-year horizon represents a complex transformation initiative that demands substantial expertise and resources. Our recommendation on an approach that best release value up to March 2028 is:

- Create a phased delivery plan by setting and communicating clear and achievable goals.
- Accelerate programme mobilisation by establishing a clear governance structure across the global community.
- Assess the existing products from vendors and developments from TSOs for use within NESO landscape. We expect value to be unlocked from these products through utilisation of Thermal DC Optimisation Assessments when used in both planning & intra-day timescales.
- We are aware of activities on NESO regarding improving data and model alignment. It is recommended that network model build for NTO solutions is engaged with these improvement activities. Input data and quality of model alignment can impact significantly on the accuracy of the output of NTO solutions.

Additional value can be gained from funding research into key areas such as:

- Development of Fast-Full AC PF and OPF solver, unlocks the ability to assess voltage constraints.
- Development of Dynamic stability assessment module, unlocks the ability to assess stability constraints.
- Development of UI and UX visualisation integrated with SCADA and EMS, maximising the use of the tool by control room operators.

Appendix

Glossary

The terminology used in this report is intended to be exact, given that NTO and its constituent vocabulary is variably defined among power system operators and in research. Terms are defined in the context of the subject of this report and sorted by alphabetically. Within each definition box, any term also referenced within the glossary is set in bold.

Term	Definition
AC PF	The mathematical formulation of both real and reactive power components incorporated in the algorithm to determine, MW, MVAr, Voltage and Angles across every node and branch in the transmission network.
Algorithm	A sequence of computational steps that, when implemented through a programming language, executes the mathematical logic of a **method**. The steps run on hardware (CPUs, GPUs).
Computation	The execution of an NTO **solver** or a constituent **algorithm**. A computation provides a result or a set of results.
DC PF	Assuming a low R:X ratio on transmission networks allows the non-linear AC power equations to be linearised. This simplifies admittance angle θ_{ij} to approximately $-\pi/2$, enabling a formulation that focuses solely on real power.
Edge	Within a **graph**, edges represent the relationship between **nodes**. For NESO's network, edges are the transmission lines where the relationship that connects the components is **PF**.
Graph	A visual representation of a network as **nodes** and **edges**. For NESO, a graph is a representation of the transmission network. Graphs are also represented mathematically, making them a part of **modelling**.
Method	The mathematical strategy that optimises variables within a defined **model**. Here, three types are integer methods (optimise TAs), continuous methods (optimise PF) and mixed integer methods (optimise TAs and PF together).
Model	A model is a mathematical representation of variable relationships. **AC PF** and **DC PF** model relationships between P, Q, V. Network models represent the relationships between **injections**, **loads**, and **TA**s.
Node	Within a **graph**, nodes represent entities. For NESO's network, nodes are any type of component that has **modelled TA**s, such as such as generators, load points, and buses.
NTO	Network Topology Optimisation. NTO refers to the process by an automated mathematical **solver** locates the best candidate **topologies** for improving overall power flows in the transmission network, following an objective.
PF	Power Flow. PF is category of **model** (for **AC** and **DC**) that calculates the flow of electricity across a network, when **injections** and **loads** are fixed, based on mathematical relationships between P, Q, V and θ.
Solution (*or* NTO solution)	A fully packaged technology that assists the control room in carrying out NTO. A solution includes a programmed objective and NTO **method**, validations, pre-processing and post-processing.
Solver (*or* NTO solver)	The combined mathematical and **algorithmic** system that calculates optimal **topologies**; based on an objective, **PF** and **TA** method(s), and any integrated validations. Does not include pre-processing or post-processing.
TA	Topology Action. An adjustment made to the discrete settings of a grid component. Possible TAs that can be modelled and computed within a NTO **solution** are defined on page 8.
Topology	The fixed state of a transmission network at one point in time, capturing the discrete settings of all grid components, but not **loads** and **injections**. In NTO, topologies follow from a defined **model** that has a set of allowed **TA**s.

Figure A1. A tree map of NTO's constituent methods

Note that this map is not exhaustive. Other classical mathematical, heuristic and machine learning methods exist that have been applied to NTO. This research chose to highlight these methods, based on the maturity of their application among TSOs, vendors, and in academic research, as well as for their overall practicality.

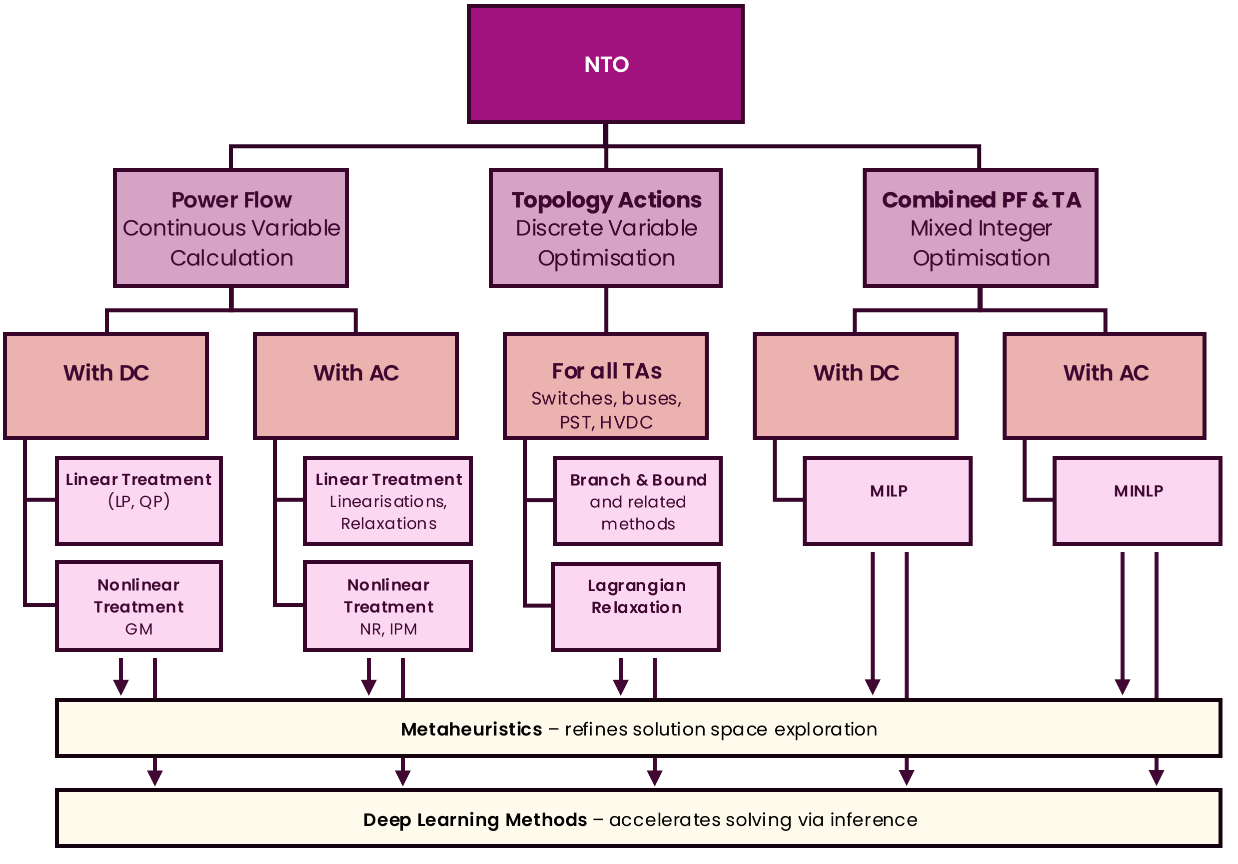

Table A1. Common Power Network Constraints that Undergo Validation

	Constraint	Description
Component-level	Thermal limits	Equipment thermal limit, measured as current (A) or P (MW).
	Voltage limits	Buses have a V limit (kV) for equipment damage, similar to thermal limits.
	Reactive power limits	Component ability to inject or absorb Q (MVAr) to maintain stable V profiles.
	Phase angle limits	Buses remain in θ bounds for injection stability; avoid uncontrolled oscillations.
	Generator limits	Limits on generator outputs, as MW and MVAr, defined by their capability curves.
Network-level	Security $(N-1,\ N-k)$	Flags component-level violations if $N-1$, , or $N-k$ components fail.
	Radiality / meshing	Describes if the topology is sufficiently interconnected and stable.
	Transient stability	Simulates escalations in θ, Q, V, or Hz in the seconds after key components fail.
	Short circuits	If network withstands abnormally high "fault" currents following a short circuit.
	Genset connectivity	Ensures generators are connected and synchronised, maintaining kV, and Hz.

Figure A2. A Modular, E2E NTO Solution with Exclusive and Optional Choices

Decomposed, an NTO solution is a sequence of modules. An arial view is critical: the modules must be paired, prioritised, and bear out computational trade-offs.

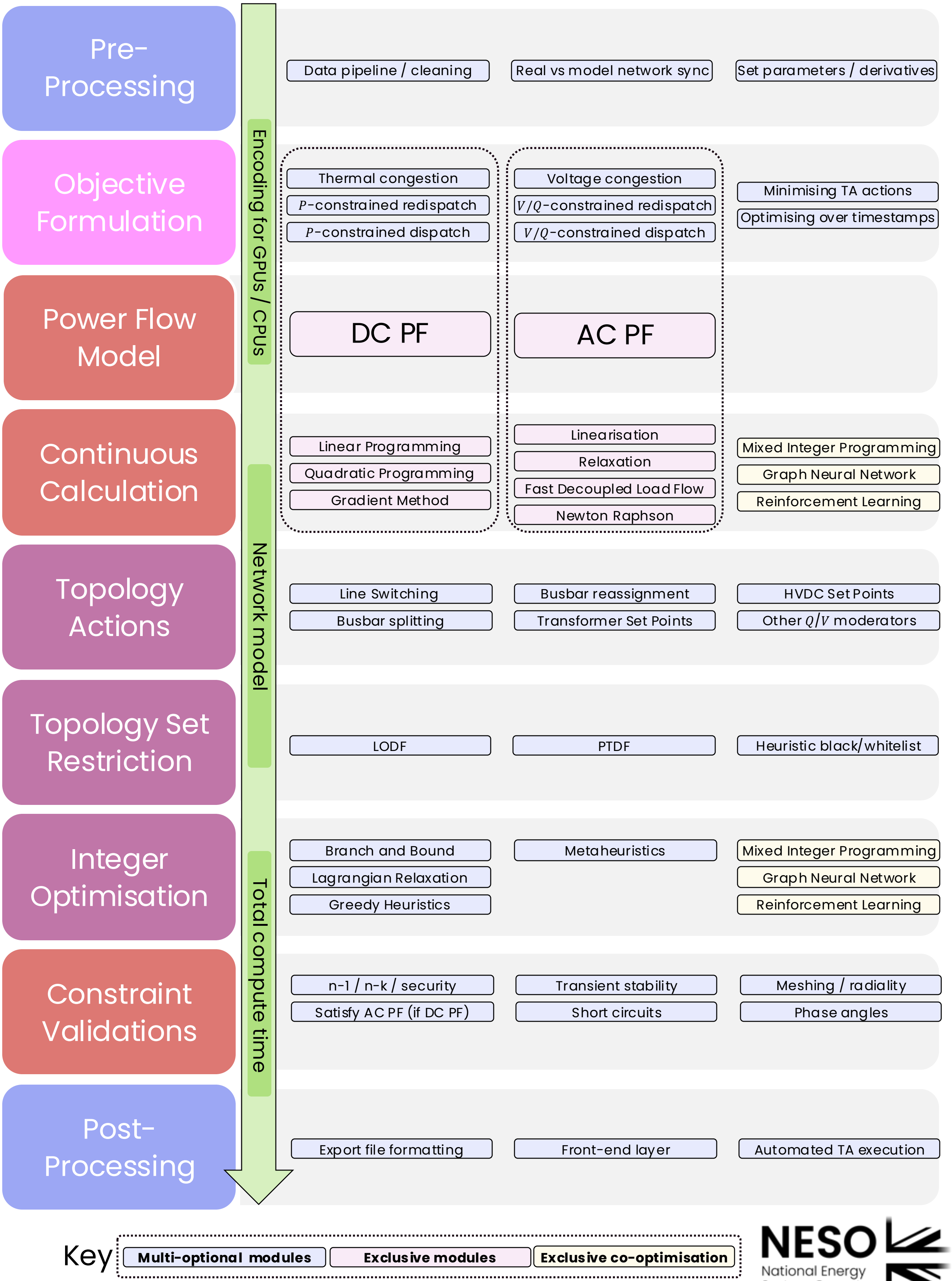

Table A2. A Simplified Assessment of Methods Across Priority Areas

Gradient descent and clustering approaches are highlighted here, as they were observed in research as screening steps within an overall solver. Gradient descent is another deep learning approach and one paper used the method in pre-solver topology set restriction (i.e. sensitivity analysis), to reduce the discrepancies between DC PF optimisation and AC PF validations.[31] Clustering approaches are a category of method within machine learning, that group data based on structural similarities, making it useful for identifying regions of a network that have common violations, or repeated TA arrangements that lead to violations. One paper used clustering to reduce the search space, and identify areas where dispatch has marginal pricing, as well as key buses that can connect dispatch between zones.[15] Another paper used clustering to identify cardinal points that could use common topologies, to reduce total TAs and prioritise NTO investigation on difficult time periods of the day.[32]

DRL methods autonomously optimize power system topologies, effectively managing large, complex action spaces, adapting to uncertainty and adversarial conditions, and often surpassing traditional or expert approaches. Pre-training with imitation learning,[28] action space reduction,[29] and GNNs[30] are strategies that have further improved convergence and scalability in DRL.

	Scales to large networks	Accuracy of PF output	Ability to reach true optimum	Rapid computation	GPU compatibility	Interpretable (provable)	Compatible to multi-obj.	Robust to perturbation	Complexity of dev.
Deep Reinforcement Learning (DRL)									
Reinforcement Learning					GPUs are not essential for training or inference				
Graph Neural Network									
Gradient Descent									
Clustering Approaches									
Metaheuristics		NA			NA			NA	
DC Linear Treatments									
DC Nonlinear Treatments									
AC Linear Treatments	Currently mediocre, but has high potential with more research								
AC Nonlinear Treatments									
Branch and Bound		NA							
Lagrangian Relaxation		NA							
MILP									
MINLP									

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