Transmission Expansion Planning under Long-term uncertainties

Future developments in the power sector are characterised with significant uncertainty arising from various factors, such as environmental concerns, the development of new technologies, new market designs, as well as societal and political influences. In power system studies, these underlying factors can, for example, translate to uncertainties in the generation mix and the electrical demand. Furthermore, long-term uncertainties are multi-dimensional as each source could be represented by four different characteristics – magnitude, temporal, technological, and locational.

The implications of disregarding uncertainty in transmission network expansion planning could be extremely expensive. Namely, failing to consider multiple possible long-term system development pathways could prompt premature commitments to flawed infrastructure reinforcement projects, which are large, costly, and irreversible by nature. Then, should an adverse scenario occur, it could render such investments unnecessary, leading to stranded investment costs and underutilisation of network infrastructure. Simultaneously, underinvestment in other transmission corridors could lead to network congestion and further negative externalities, including environmental implications. Therefore, it is crucial to consider several key uncertainty sources and characteristics in power system studies in order to mitigate the risk of future regret.

The theory and studies presented here have previously been published in scientific literature, as listed below. For further information and details, the reader should refer to:

- S. Borozan, S. Giannelos, and G. Strbac, “Strategic Network Expansion Planning with Electric Vehicle Smart Charging Concepts as Investment Options”, Advances in Applied Energy, 2022
- S. Borozan, S. Giannelos, M. Aunedi, and G. Strbac, “Option Value of EV Smart Charging Concepts in Transmission Expansion Planning under Uncertainty”, IEEE MELECON, 2022

Representation of uncertainty for expansion planning

Future developments in global power systems are often depicted using long-term projections or scenarios. For instance, in Great Britain (GB), National Grid ESO outlines four potential pathways known as ‘Future Energy Scenarios’ (FES): Leading the Way, Consumer Transformation, System Transformation, and Steady Progression. Each scenario makes specific assumptions about various sources of uncertainty, such as wind and solar capacities, energy storage penetration, and peak electrical demand. The formulation of the FES involves thorough research into current trends and detailed consideration of technological, economic, social, and political factors to create well-informed assumptions.

However, relying on just four scenarios to represent future system pathways can be somewhat restrictive. By concentrating on one or several sources of uncertainty, it is possible to expand the FES into multiple scenarios for a more comprehensive analysis. For example, if the study's focus is on assessing the impact of electric vehicle (EV) adoption and the strategic role and value of smart charging concepts in the development of the GB power system, then uncertainties regarding the extent, timing, and location of EV penetration can be represented in greater detail throughout the planning horizon. Additionally, the expansion study could delve into technology-specific uncertainties, such as charger power ratings, economic uncertainties like charger investment costs, and behavioural uncertainties, such as participation rates in smart charging schemes. These elements could enhance the FES, effectively broadening them into a series of distinct scenarios.

Scenario trees to describe long-term developments

Long-term uncertainty can be effectively represented using a scenario tree, which offers a coherent visualisation of how uncertainty unfolds across various system parameters. Constructing a scenario tree involves expert opinions, industry insights, and detailed analyses of market dynamics. While two-stage scenario trees are most commonly used, they provide limited recourse options in the target year. On the other hand, multi-stage formulations offer greater flexibility in decision-making and facilitate the development of comprehensible long-term investment strategies.

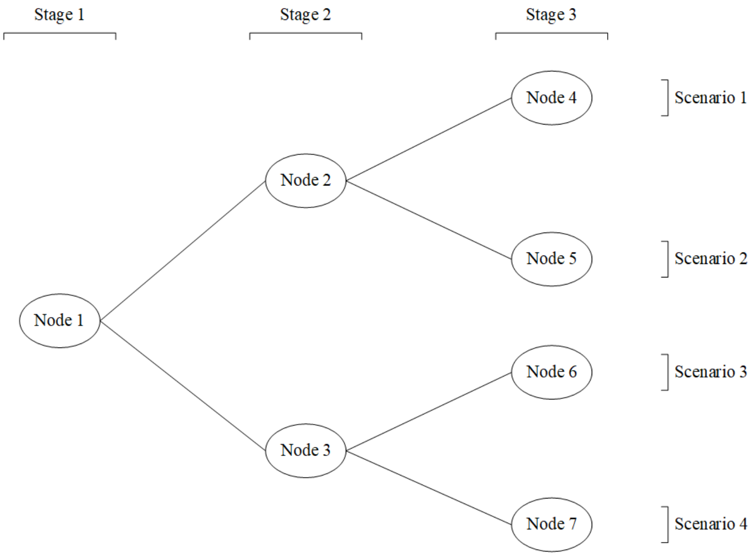

Figure 1 Scenario tree representation of long-term uncertainty

Short-term operational variability

For short-term variability, each node of the scenario tree incorporates representative blocks of system operation. These blocks involve hourly factors that characterise system operation parameters such as electric demand, EV charging, and the output of renewable generators. This method ensures that operational variability is accurately represented while keeping the problem size manageable.

Planning framework

Transmission expansion planning is generally approached as a centralised decision-making problem aimed at minimising both the capital expenditure for new or reinforcement projects and the operational expenditure related to system operation. Industry-standard methods often rely on Net Present Value (NPV) investment theory within a Cost-Benefit Analysis framework, typically driven by a central forecast with accompanying sensitivity studies. However, these deterministic planning methods have proven inadequate for addressing the investment needs of modern power systems, which are characterised by uncertainties inherent in the energy transition.

The framework described here represents a contemporary method for decision-making under uncertainty. As described in Figure 2, this framework incorporates various system and investment parameters as inputs. It employs stochastic optimisation, models smart technologies as investment alternatives, and ultimately provides a comprehensive investment strategy along with the valuation of smart options as outputs.

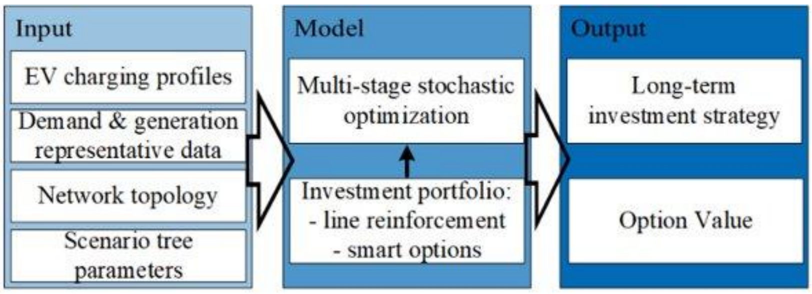

Figure 2 Framework for transmission expansion planning under uncertainties

Multi-stage stochastic optimisation

Decision-making under uncertainty can be approached through various optimisation methods, with stochastic optimisation being particularly prominent. The most commonly used formulation is a two-stage stochastic problem. In this setup, the first stage represents the current state of the system, while the second stage encompasses different potential system configurations in a future target year. Investment decisions are made in the first stage, and system operation decisions are made in the second stage, allowing for some corrective actions in response to the realisation of uncertainties.

A multi-stage stochastic formulation, as discussed earlier, involves making optimal decisions across multiple stages. This approach captures the inter-temporal resolution of uncertainty and provides opportunities for strategic actions throughout the planning horizon. Therefore, a multi-stage expansion planning framework is essential for flexible decision-making in the face of increasing uncertainty, as it facilitates a shift from a “now-or-never” investment mindset to a “wait-and-see” strategy.

Flexibility options

Network infrastructure projects are bulky, carry large capital costs, and are subject to various environmental considerations and lengthy permitting processes. In contrast, investing in non-network or smart solutions that optimise the utilisation of existing infrastructure can be quicker, less cumbersome, and potentially more cost-effective than traditional reinforcements. These non-network solutions include alternatives that mitigate line congestion and demand curtailment in the short or long term, thereby deferring or displacing the need for new line investments. Common options include energy storage, demand response, and flexible AC transmission system (FACTS) devices.

Incorporating flexible technologies into the investment portfolio can significantly enhance a planner’s strategic decision-making ability to hedge against uncertainty. Their primary advantage lies in the ability to delay conventional reinforcement until there is at least partial resolution of uncertainty, allowing for a 'wait-and-see' approach. This approach involves making an initial decision between irreversible conventional reinforcement and flexible solutions that provide the option to invest in the network at a later stage if needed. Should network reinforcements become necessary in the future, the smart option would have already served its short-term purpose as a hedging tool against uncertainty. Additionally, it would provide long-term operational flexibility, thus addressing the increased need for flexibility in modern power system operations.

Solution algorithm

The outlined planning approach enables a more comprehensive consideration of key uncertainties in transmission expansion studies, thereby reducing risk exposure by accounting for a wider range of possibilities. However, this method faces a significant trade-off between modelling complexity and the computational performance of state-of-the-art models. Given the large-scale nature of network expansion planning, there exists a threshold at which the problem becomes intractable. To address this, data-driven methods and machine learning techniques could be employed for scenario selection and to enhance optimisation performance. These approaches can help mitigate tractability issues while providing a detailed representation of long-term uncertainty.

The multi-stage transmission expansion planning approach described here is treated as a large-scale mixed-integer linear programming (MILP) problem, which often becomes intractable, particularly when dealing with extensive scenario trees. However, the problem's structure lends itself well to decomposition via Benders Decomposition. Specifically, the problem can be divided into an investment master problem (M-P) and multiple system operation subproblems (S-Ps) that correspond to each combination of scenario tree nodes and short-term operation blocks. The MILP M-P include all the mixed-integer variables from the original problem, whereas the S-Ps are instances of linear programming. This decomposition facilitates handling the problem's complexity and enhances computational feasibility.

Figure 3 describes the iterative process, in which the M-P yields a candidate solution, then the investment decisions are fixed and passed to the S-Ps that are now free from any integer decision variables and represent independent problems that can be solved in parallel. Using dual variables from the S-Ps, so-called Benders optimality cuts are generated and appended to the M-P in the following iteration, which improves its approximation of system operation costs, thus bringing it closer to the optimal expansion decisions. As such, the M-P is a relaxation of the original problem that approximates operation costs and is built up over iterations using such optimality cuts. The method converges, in a finite number of iterations, when its upper and lower bounds are equal or within a predefined tolerance.

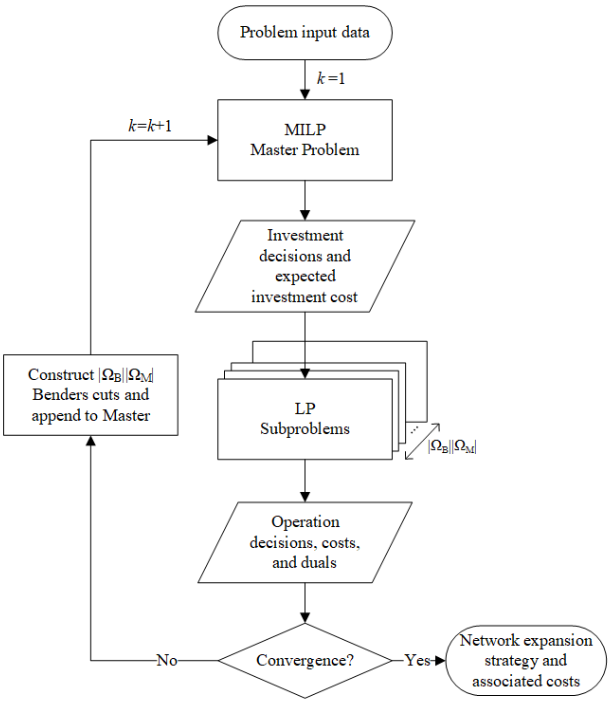

Figure 3 Solution algorithm based on Multicut Benders Decomposition

Example case study

Assumptions

This example of the long-term planning of the GB transmission network serves to demonstrate the concept of planning under uncertainty and investment flexibility. The corresponding network is shown in Figure 4. To keep in line with the realities of the GB power sector, the FES developed by National Grid ESO are used as a base for modelling uncertainty. The development of FES involves an extensive and detailed consideration of current trends to make well-informed assumptions based on technological, economic, social, and political considerations. There are four proposed scenarios: Leading the Way (LW), Consumer Transformation (CT), System Transformation (ST), and Steady Progression (SP). The plots in Figure 5 and Figure 6 summarise the current and projected generation capacity and demand in 2020, 2030, 2040 and 2050. Figure 7 shows the FES assumptions on the total number of cars and residential EVs in GB.

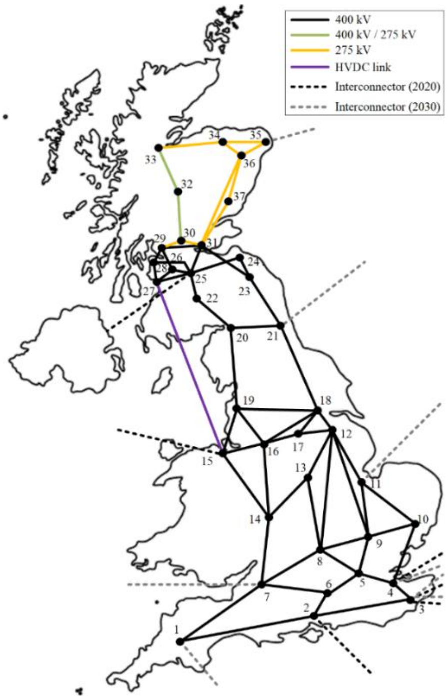

Figure 4 Reduced transmission network of Great Britain

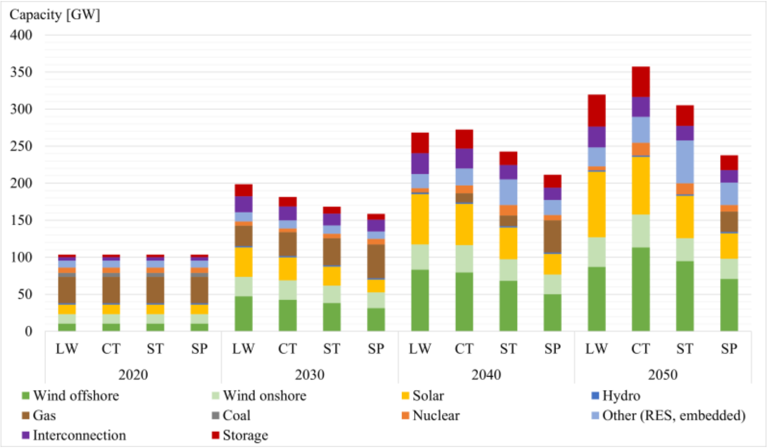

Figure 5 FES projections for GB generation capacities per technology type

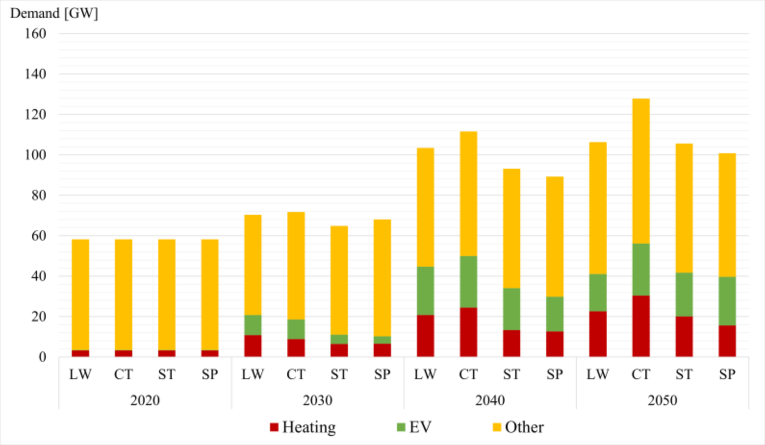

Figure 6 FES projections for GB peak demand per type

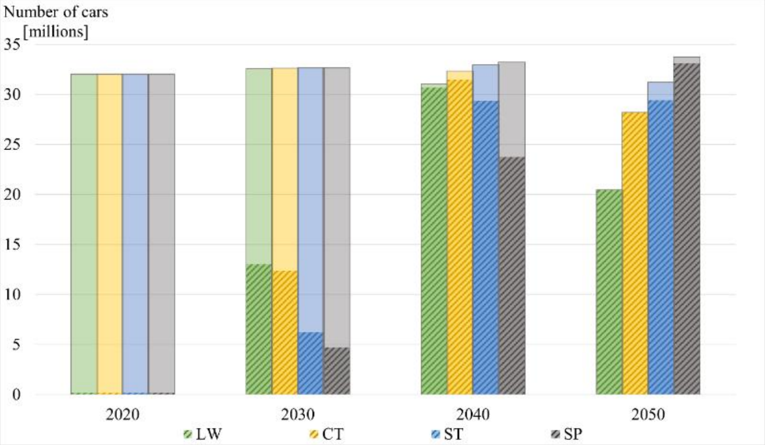

Figure 7 FES projections for number of cars (all types) and electric vehicles in GB

Here, the uncertainty within FES is expanded to include the timing and extent of EV uptake and the unit investment cost for smart chargers. This study spans 16 distinct scenarios over a 40-year horizon, divided into four 10-year stages. Figure 8 illustrates the corresponding scenario tree, where nodes are color-coded to differentiate among the four base FES scenarios: green nodes represent the LW scenario, yellow nodes correspond to the CT scenario, blue nodes signify the ST scenario, and grey nodes pertain to the SP scenario. The first stage reflects the system state based on 2020 data, the second stage pertains to decision-making in 2030, the third in 2040, and the final stage in 2050. Each scenario tree node displays its state probability, percentage of residential EVs compared to the corresponding assumption in FES (striped bars in Figure 7), and smart charger unit investment costs (given in the form £x ; £y, where x corresponds to G2V chargers and y to V2G and V2B chargers).

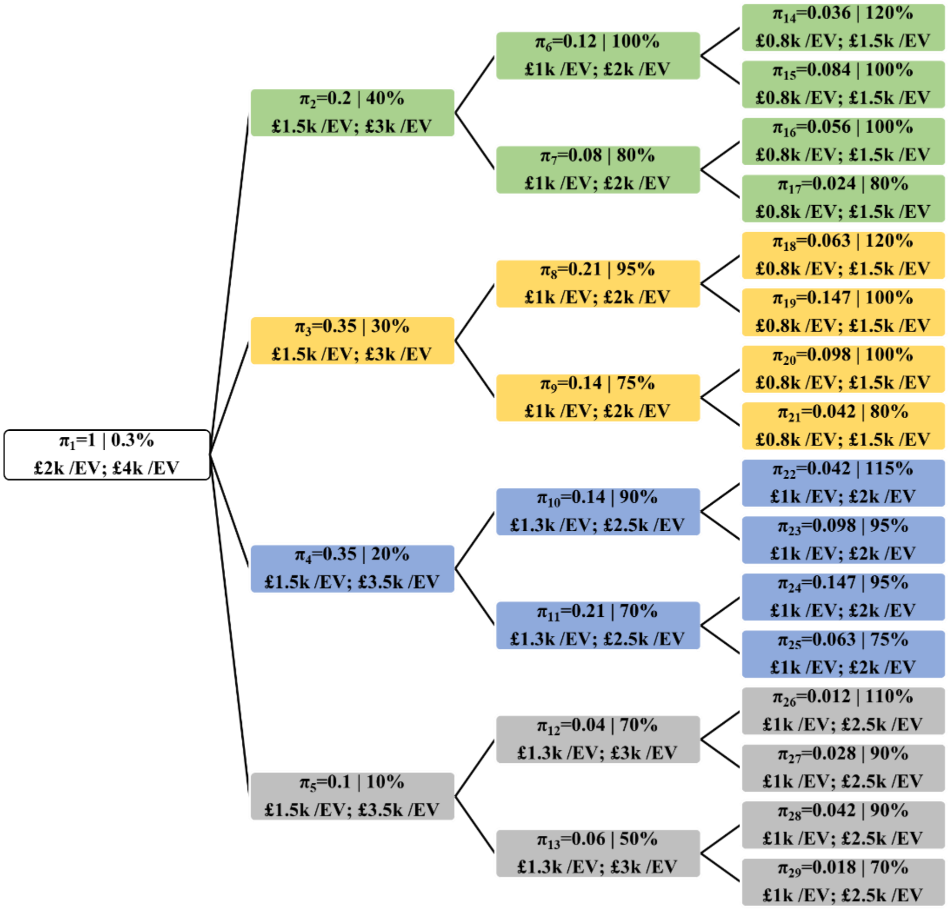

Figure 8 Scenario tree describing long-term uncertainty for the expansion planning of the GB transmission system with a focus on EV uptake

The residential EV fleet is assumed homogeneous. The assumed energy capacity of EVs is 50 kWh and the charging power rating is 7.4 kW, which is consistent with the FES modelling and the currently available mid-size EVs. The system operation problem is solved for eight representative days, one workday and one weekend day per season, to capture both seasonal variations and weekly driving patterns.

The considered smart (non-network) investment options in this study are three different concepts of EV smart charging (SC). Specifically, these are Vehicle-to-Grid (V2G), Grid-to-Vehicle (G2V), and Vehicle-to-Building (V2B). Figure 9 describes how the aggregated electrical load for charging under these concepts would differ from the fixed uncoordinated charging load, and therefore, the reason they would be suited for congestion management and viable as an investment alternative to network reinforcement. For the purposes of V2G and V2B modelling, the lower limit on SoC is 30 % of the total capacity, while vehicles charge and discharge with 90 % efficiency. Finally, in the case of V2B, it is assumed that there are two EVs for every house with a 4.6 kW peak demand.

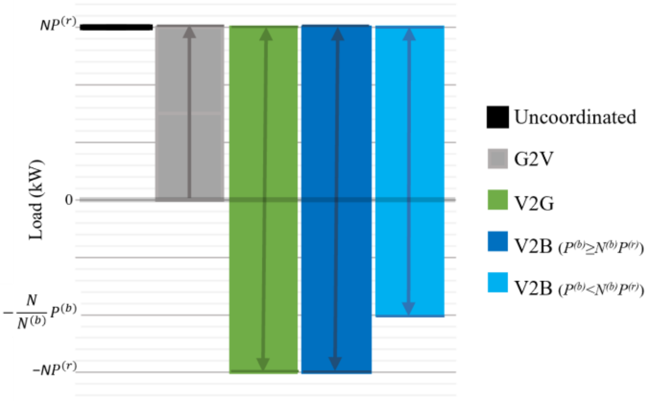

Figure 9 Visualisation of the differences between uncoordinated charging and three smart charging concepts with respect to the controllable load range of N aggregated vehicles

Results

The study reveals that the expected total system cost is £94.7 billion, that is the weighted average of investment and operation costs across all considered scenarios. But the results strongly suggest that planning the expansion of the GB power system with any SC concept generates substantial economic savings with respect to the conventional-only case. The Option Value (OV) is the economic net benefit of the option to invest in a smart alternative to network reinforcement. The results show that the OV of G2V amounts to over £1.2 billion, V2G achieves an OV of £10.7 billion, and the OV of V2B is £10.1 billion. The sources and drivers for this OV are explored in following.

The obtained investment decisions are shown for all cases in scenario tree form in Figure 10, where [x-y] denotes the transmission corridor between network buses x and y, c(·) is a list of buses where smart charger investments are made, and {z} denotes the number of smart charger investments in the corresponding node.

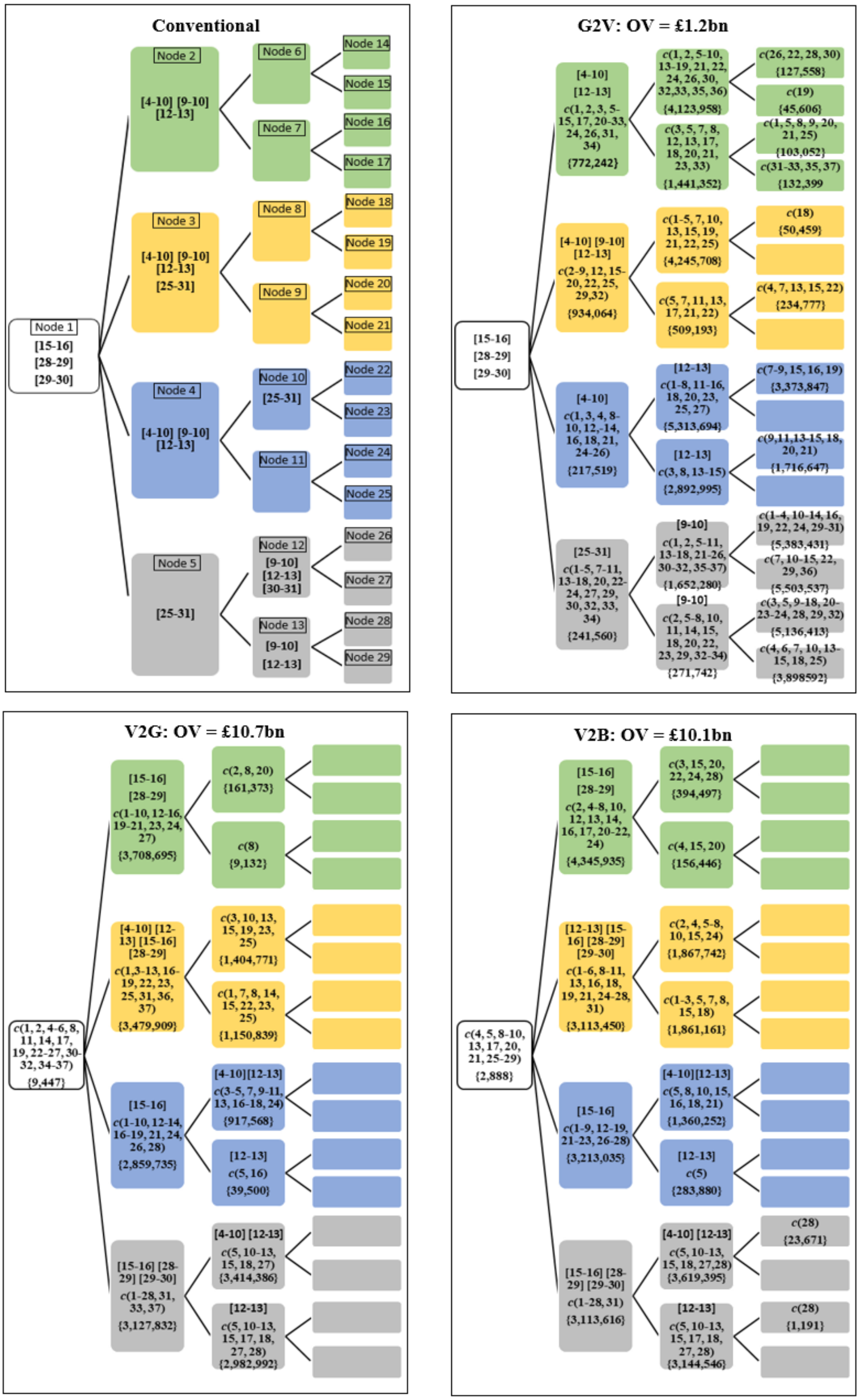

Figure 10 Expansion decisions obtained with each of the four investment portfolios

In addition to facilitating system operation cost savings, SC concepts are crucial in providing investment flexibility amid long-term uncertainty. The stochastic planning framework aims to generate the probability-weighted optimal solution across all considered future realisations. In this example, scenarios share up to three common nodes within the scenario tree, with the root node being common to all scenarios. For the GB network expansion planning relying solely on conventional reinforcements, three transmission corridors necessitate immediate capacity upgrades (at node 1) to accommodate anticipated future demand increases. Subsequent reinforcements are required in later stages, contingent on the realisation of uncertainty. Investment decisions at these critical junctures impact multiple scenarios and could potentially lead to stranded investments in certain future outcomes.

Figure 11 (top) illustrates the total network capacity investment, while Figure 11 (bottom) the corresponding conventional reinforcement costs for each scenario, following the stochastic expansion strategy utilising only conventional reinforcements, as presented in Figure 10. Instances of overinvestment are highlighted in both figures, revealing stranded costs in all scenarios except the first and the fifth. Overinvestment is assessed relative to the optimal deterministic expansion decisions for each scenario, where the issue of common nodes is irrelevant, as the deterministic approach presumes perfect foresight of the future. The risk of capacity overinvestment associated with planning with only conventional reinforcement, calculated as the sum of probability-weighted stranded costs across all scenarios, totals £132,939,306.

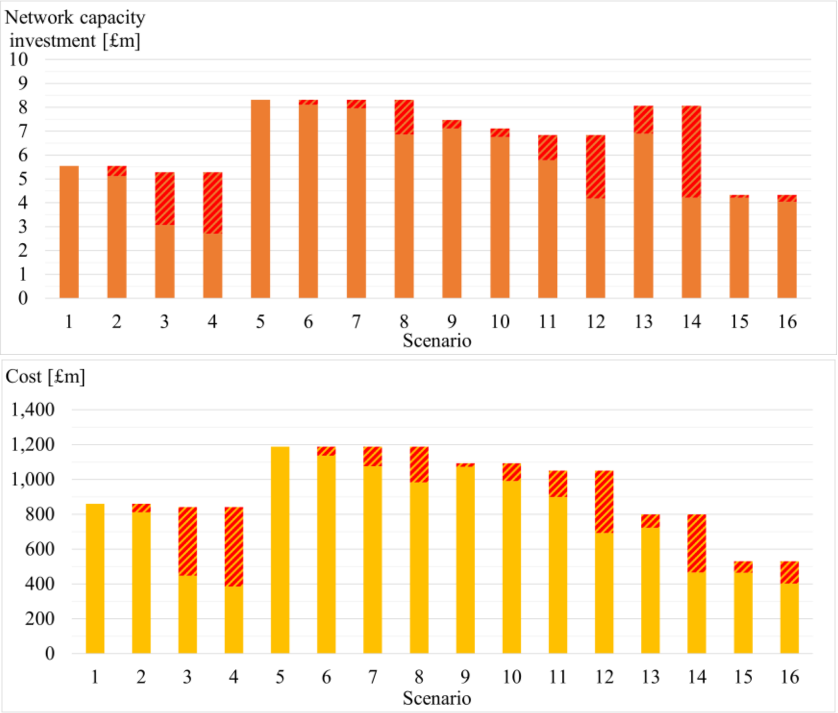

Figure 11 Total network capacity investment and conventional reinforcement costs per scenario following the stochastic expansion strategy with only conventional reinforcements. Red stripes indicate the amount that is overinvested.

The role of SC options in providing investment flexibility and mitigating the risk of capacity overinvestment becomes evident when analysing the common nodes in Figure 10. For G2V, although conventional investments at the root node remain, strategic smart charger placements significantly impact reinforcements in stages 2 and 3. Specifically, the reinforcement of one transmission corridor is avoided in nodes 2, 3, 10, and 13, while two reinforcement projects are avoided in nodes 4 and 12. Additionally, the reinforcement of the [12-13] corridor is deferred from node 4 in the second stage to nodes 10 and 11 in the third stage.

Planning with V2G has an even stronger impact on conventional investment decisions. Notably, the need for immediate investments at node 1 is eliminated as strategic V2G charger investments defer these reinforcements to the second stage after some uncertainty has been resolved. Furthermore, the [29-30] corridor appears only at node 5, indicating that its reinforcement is necessary only for scenarios 13 to 16. Investment projects [28-29] and [29-30] are absent from node 4, and thus, not undertaken under this uncertainty realization in stage 2. These deferrals from node 1 significantly mitigate overinvestment, as investment decisions affecting all scenarios are avoided. V2G also displaces three conventional projects in node 2, two in node 3, and one each in nodes 4, 5, and 12. Lastly, reinforcements of [4-10] and [12-13] are deferred from node 4 to node 10, with only [12-13] appearing in node 11.

V2B achieves a similar impact on conventional investments as V2G, with the only difference observed in node 3. However, the number of V2B charger investments is higher than V2G across all scenarios, leading to higher expected investment costs and a lower OV. Despite decreasing unit costs and increasing participation factors in subsequent stages, the majority of V2G and V2B investments occur in stage 2, indicating that their benefits outweigh the high costs even at relatively low participation rates. Conversely, while G2V deployment is observed as early as stage 2, most investments happen in stages 3 and 4.

Figure 12 shows the total network capacity investment for each scenario following the stochastic expansion strategy with different SC options. The first observation is that all SC concepts can substitute a substantial amount of conventional capacity investment seen in Figure 11. Notably, V2G and V2B completely eliminate stranded capacity observed when planning only with conventional reinforcements. However, transmission capacity overinvestment appears in two scenarios when planning with G2V, resulting in stranded investment costs of just under £206 million and £269 million for scenarios 3 and 4, respectively. Despite this, integrating G2V into the planning portfolio significantly improves over the conventional approach, reducing the risk of capacity overinvestment, as defined previously, by 86% to £18 million.

The residual overinvestment with G2V likely stems from its inability to displace the transmission capacity required for the rapid and extensive electrification of transport in scenarios 1 and 2. Figure 7 shows that the number of EVs in the LW scenario, corresponding to scenarios 1 to 4, rises sharply until 2040 before dropping significantly in 2050. Meanwhile, non-EV electrical demand remains relatively stable between 2040 and 2050, as shown in Figure 6. Consequently, stage 4 has a lower peak demand than stage 3, meaning that a proportion of capacity upgrades made to meet the rapid demand increase by stage 3 becomes underutilised in stage 4. Unlike G2V, V2G and V2B investments can substitute over 4 GW of transmission capacity upgrades in these scenarios, thereby eliminating the risk of capacity overinvestment and mitigating the underutilisation of assets.

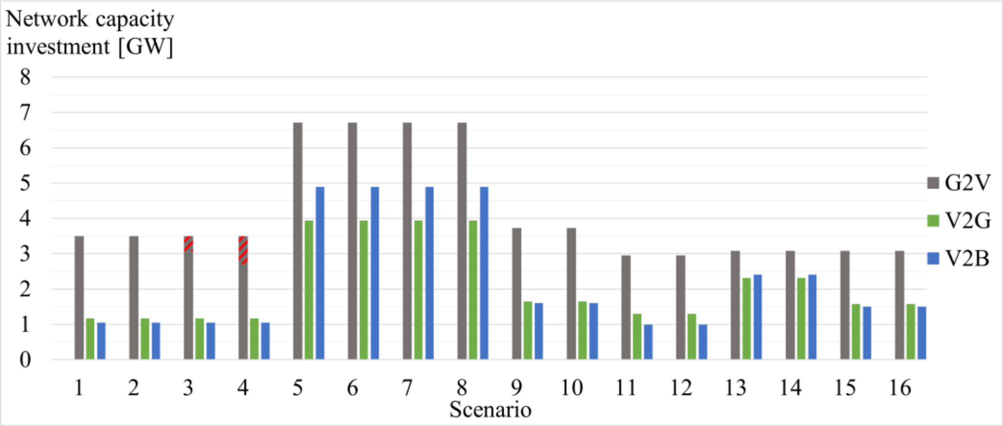

Figure 12 Total network capacity investment per scenario following the stochastic expansion strategy with smart charging concepts. Red stripes indicate the amount that is overinvested.

Conclusion

Several key observations can be made from the example presented here:

1. With a stochastic planning framework, the necessary investments are always undertaken but they can be strategically delayed until (some) uncertainty has been resolved.

2. Investment flexibility is enhanced with the integration of smart investment options. They allow:
   a. better transmission assets utilisation
   b. displacement or deferral of conventional network infrastructure projects to a later stage
   c. mitigation of the risk of overinvestment
3. *EV smart charging concepts* are viable investment options when facing long-term uncertainties with a large Option Value.
   a. Bidirectional charging is notably more valuable than unidirectional charging.
   b. There are significant system operation savings and wider system benefits.

Contribution to development and use of low carbon technologies, sustainability and circularity

The topic of power system planning under uncertainty is greatly important for the development of low carbon technologies. This is because implementing a planning framework, such as the one presented here, recognises the full value of low carbon and flexibility assets. As such, it helps the planner make more informed investment decisions and promotes the use of these technologies, both as network assets and as tools for hedging against uncertainty. In the long term, this would boost the integration of technologies that support sustainability of the grid in a cost-effective manner.

Highlight on application in industry

On one hand, there are multiple stakeholders in the power sector that are directly involved in or have interest in the long-term development of the power systems. These could include, for instance, system operators, transmission or distribution owners, regulators, consultancies, generation companies, technology developers, and so on. On the other hand, incumbent planning methods based on deterministic optimisation and cost-benefit analyses need to evolve in order to properly tackle the risk of decision-making under uncertainty and to facilitate the integration of low carbon technologies. This topic represents a fundamental resource for the implementation of an advanced framework and the drivers for strategic planning under uncertainty, which can help future-proof the applied planning methods in industry.

Contribution to development of skills and competences

As elaborated in the previous subsection, the topic could inform many stakeholders of the importance and possibilities of the implementation of a stochastic optimisation-based planning framework. The knowledge shared in this tutorial could enhance the understanding and competencies of employees in multiple areas, including:

- The importance of considering uncertainty in long-term planning
- The characteristics of long-term uncertainties and their model-based representation
- The general overview and requirements of a stochastic planning framework
- The possibilities of strategic decision-making
- The role of non-network flexibility assets
- Etc.

Due to the complexity and breadth of the topic, this training does not present in detail the implementation of advanced planning methods. It should therefore be considered as an introduction to the topic that delivers the fundamental knowledge required for upskilling the workforce in planning methods.