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Energy Innovation Needs Assessment: Energy Networks

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Authors

The 2025 Energy Innovation Needs Assessment: Energy Networks report was commissioned by Innovate UK and DESNZ and was delivered by a consortium led by the Carbon Trust, including Mott MacDonald, UCL and Pengwern Associates.

Carbon Trust was the lead technical author for the energy networks technology theme report.

Views expressed in this report are those of the authors and not necessarily those of the UK Government.

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Abbreviations

CBA	Cost Benefit Analysis
CCS	Carbon Capture and Storage
CCUS	Carbon Capture Utilisation and Storage
CreDo	Climate Resilience Demonstrator
CNI	Critical National Infrastructure
D/TNOs	Distribution/Transmission Network Operators
DFS	Demand Flexibility Service
DFTs	Distributed Feeder Technologies
EHVDC	Extra High-voltage Direct Current
EINAs	Energy Innovation Needs Assessments
ENA	Energy Networks Association
EVs	Electric Vehicles
FES	Future Energy Scenarios
GVA	Gross Value Added
highRES	High spatial and temporal Resolution Electricity System
HVDC	High-voltage Direct Current
iDNOs	Independent Distribution Network Operators
IGEM	Institution of Gas Engineers and Managers
LCTs	Low-Carbon Technologies
LDES	Long Duration Energy Storage
NESO	National Energy System Operator
NIA	Network Innovation Allowance
NIC	Network Innovation Competition

NZIP	Net Zero Innovation Portfolio
PNDC	Power Networks Demonstration Centre
R&D	Research and Development
R&I	Research and Innovation
STATCOM	Static Synchronous Compensator
SIF	Strategic Innovation Fund
SMRs	Small Modular Reactors
TEG	Technical Expert Group
UK TIMES	The Integrated MARKAL-EFOM System

Key findings

Key findings (not in order of priority)

1 Innovation strategies must adopt an integrated systems approach to address the multifaceted challenges of gas decarbonisation, electrification, and energy security. A holistic view is essential to optimise the interactions between different energy vectors and ensure seamless operation. This approach will enable more efficient use of resources and facilitate the integration of renewable energy sources.

2 Uncertain network states demand optionality and openness. There is considerable uncertainty in network transitions, highlighting the need for flexible and open innovation pathways. The future energy landscape is highly dynamic, and multiple scenarios must be considered. An agile approach to innovation, one where system development iteratively shapes network priorities.

3 Strengthen investor confidence and steer innovation with clear, focused direction in gas networks to ensure successful integration and resilience. By providing targeted support and strategic guidance, the UK can effectively manage the transition towards decarbonisation, enhancing the reliability and efficiency of gas networks. This focused approach will also foster greater collaboration and innovation, ultimately contributing to a robust and sustainable energy system.

4 System-wide innovation coordination is at a critical point. The sector currently lacks cohesive and coordinated approaches, which are essential for guiding innovation through complex stakeholder and system requirements. Clear leadership and governance structures are needed to align efforts, avoid duplication, and ensure that innovation initiatives are effectively implemented and scaled.

5 Addressing the technological, social, and economic dimensions of network innovation is crucial for achieving Net Zero targets. This report emphasises the importance of consumer-centric approaches and the need for clear policy signals to drive market momentum. Robust policy frameworks and financial incentives are required to stimulate innovation and de-risk investments in new technologies.

The UK's energy networks must undergo strategic innovation to meet Net Zero targets, enhance system resilience, and coordinate fragmented energy system development. The UK's energy networks are under immense pressure to adapt to challenging future needs, especially in the context of achieving Net Zero targets and strategic innovation is essential to meet these goals at the required pace and scale. The growing demand for electricity, coupled with the need to decarbonise gas networks and ensure energy security, requires an integrated approach to innovation. By their very nature and function, networks are the nexus of the energy system, connecting suppliers, consumers, and technologies. Their role is paramount in achieving a Net Zero future, however, the rapid pace required for this transition places immense pressure on networks, resulting in increasing levels of network constraints.

This report assesses key innovation needs in UK energy networks to meet Net Zero targets, enhance system resilience, and coordinate fragmented energy system development. The report identifies priority areas and technologies that can drive necessary transformation, emphasising the importance of strategic innovation to accelerate a resilient energy system. Key innovation needs include advancements in transmission and distribution technologies, digitalised control systems, cybersecurity, and whole system coordination around the future role of gas networks. Technologies in focus represent high-priority innovation areas that are essential to accommodate the growing demand for electricity, decarbonise gas networks, and ensure energy security.

The underlying analysis was conducted through a comprehensive examination of the current state of network innovation, a review of relevant policies and strategies, and consultations with industry experts. The methodology involved stakeholder workshops, interviews, and surveys to gather a wide range of perspectives and validate findings. The EINAs framework was used to prioritise technologies based on their potential impact on achieving Net Zero targets, energy security, technology readiness (commercial and integration readiness levels also included), and suitability for public support or funding. Findings were further complemented by economic analysis using deployment profiles and business opportunities calculators to assess the potential Gross Value Added (GVA) and job creation associated with the prioritised technologies.

Through this process, we identified 11 high-priority technology areas suitable for public funding support, with significant potential to impact the achievement of Net Zero. The prioritisation framework ensured a balanced approach, considering both immediate and long-term innovation needs to support the UK's energy transition. Out of the 64 technology areas evaluated, technologies that provided enhanced network capacity featured heavily within high-priority innovation areas. Medium and lower prioritisations, while enabling technologies that are crucial for broader system development, do not present immediate or critical innovation needs for meeting Net Zero targets.

The wider energy system implications based on the identified innovation needs highlight the necessity for an integrated approach to network innovation. This approach must consider the interactions between different energy vectors, such as gas decarbonisation, electrification, and energy security, to optimise resource use and facilitate the integration of renewable energy sources. The report underscores the importance of flexible and open innovation pathways to navigate uncertainties in network transitions and system development. By adopting a holistic view, the energy system can achieve more efficient use of resources through strategic innovation focal points, ultimately supporting the UK's ambitious targets. This integrated approach will enable the energy system to adapt to future demands, evolving landscapes, and network configurations with while maintaining investor confidence.

The report highlights the potential of a few key high-priority technologies like second-generation cables (e.g. high temperature superconducting (HTS) cables), dynamic line rating (DLR), and distributed feeder technologies (DFTs) to significantly impact the UK's energy networks. Innovations in HTS cabling can address the need for enhanced grid capacity and improved energy efficiency, making them a practical choice for modernising grid infrastructure while DLR, increasingly a BAU technology, can enhance grid flexibility and reliability, accommodating the variable nature of renewable energy sources and mitigating congestion. DFTs are part of advanced power electronics and management, managing voltage and thermal congestion to improve power quality, and support the integration of low-carbon technologies (LCTs) like electric vehicles and heat pumps. By optimising the use of existing assets and deferring costly network reinforcements, DFTs can significantly enhance the capacity and reliability of distribution networks. The successful innovation and subsequent integration of these technologies, as with other high-priority technology areas, will play a crucial role in modernising the UK's energy infrastructure and supporting the transition to a low-carbon economy.

There are substantial business opportunities associated with deploying the aforementioned high-priority technologies. The report projects that innovation in HTS, DLR, and DFTs could cumulatively contribute between £0.20bn and £1.15bn GVA by 2050. This is without accounting for wider beneficial economic impacts, as the deployment of these technologies is expected to drive significant improvements in network performance, support broader system development, ease the deployment of other technologies within the EINAs, and create skilled jobs in research, engineering, and technology innovation. The economic analysis underscores the importance of public support and comprehensive innovation strategies to stimulate market momentum and de-risk investments in new technologies. By investing in all priority areas, the UK can enhance its competitive advantage in the global energy market and ensure a sustainable and resilient energy system.

Innovative technologies can reduce the size and cost of required transmission infrastructure, with higher levels of innovation leading to lower costs and less infrastructure needed. Our analysis results indicate that increasing levels of innovation across technologies in focus can reduce transmission costs by 6% to 10%, by 2050. However, a coordinated approach to network innovation is needed with clear leadership and governance structures to align efforts and ensure effective implementation and scaling. By addressing the technological, social, and economic dimensions of network innovation, the energy system can achieve greater resilience and reliability. The report further purports the need for robust policy frameworks and financial incentives to drive market momentum and support the widespread adoption of innovative solutions.

To further refine feasible innovation routes and push the UK energy system innovation forward, the report recommends adopting an integrated systems approach, maintaining optionality and openness, and enhancing system-wide innovation coordination. Strategic investments in priority technologies will offer the greatest potential for accelerated impact, driving significant improvements in network performance and supporting the broader energy transition. By fostering collaboration among stakeholders and ensuring clear policy signals, the UK can create an environment conducive to continuous innovation which actively contributes to achieving national economic and decarbonisation targets. Coordinated efforts between Ofgem, DESNZ, Innovate UK, and other key stakeholders are essential to align innovation initiatives and drive transformative solutions.

The report is structured to provide actionable insights and recommendations that are easily digestible. Infographics and bolded key points guide the reader through the prioritisation process and highlight the critical takeaways. The report also includes appendices with detailed evidence sources for readers who wish to delve deeper into specific topics.

The technologies selected and overall recommendations in this report are results of independent research and do not represent UK Government policy.

Overview of network innovation

Key Chapter takeaways

- The UK's network evolution is driven by gas decarbonisation, rapid electrification, and energy security, requiring an integrated systems approach.
- Innovation must be flexible to navigate uncertainties in network transitions and system development.
- Currently, the sector lacks cohesive innovation strategies, resulting in innovation fragmentation. Clear leadership and governance are needed to manage stakeholders and system complexities.
- The EINAs programme and this report aim to focus and drive innovation in network strategies.

Introduction

Research, development, and deployment of innovations is essential to meet climate goals. Public funding can address market failures and boost emerging technologies. By investing in areas with limited market momentum, these interventions can speed up the adoption of innovative solutions and keep the UK at the forefront of energy technology. Public funding intervention, a core focus in this report, is crucial for innovation where market forces alone are insufficient, ensuring progress beyond existing initiatives.

The Energy Innovation Needs Assessments (EINAs) have been developed and updated to identify key innovation needs across the UK's energy system, to provide an evidence base for the prioritisation of investment and support for clean energy innovation. The 2025 publications reflect an update on the 2019 exercise, accounting for the significant changes and progress both in the clean energy sector and the wider economy. To complement and build on the UK's Net Zero Research and Innovation Framework, the updated EINAs will inform key decisions on clean energy innovation funding through a structured evidence base that quantifies and assesses the role and scale of opportunities. The evidence enables comparison across technologies and takes account of wider factors that may impact deployment and scale-up.

This report focuses on and emphasises the importance of energy networks, shifting from a barrier-focused to an enabler-driven approach to assess critical grid technologies for Net Zero targets. The analysis was informed by extensive engagement with experts and innovators, and has informed analysis across other EINA sectors. Other EINAs reports and related modelling have in turn been used iteratively to inform the energy networks report and ensure cohesive assessment of innovation needs. This report aligns with the future system shaped by other supply/demand-side EINAs and is referenced where applicable in each report. This report details:

- key methods (*Prioritisation methodology*) for prioritising technologies and innovation areas
- provides key findings for shortlisted high-priority technologies (*Prioritised network technologies*)
- discusses selected technologies in depth (*Technology deep dives*)
- economic opportunities related to three selected technologies (*Business opportunities in electricity networks*)
- Network-specific innovation needs are integrated with system and sectoral findings

The 2025 EINAs publications have been commissioned by DESNZ and produced by a consortium led by the Carbon Trust, including Mott MacDonald, UCL and Pengwern Associates. The Carbon Trust was the lead technical author for the Networks sub-theme report. In addition to DESNZ, Innovate UK commissioned the Energy Networks report.

Scope and Limitations of the EINAs:

The EINAs project is a research exercise to evaluate the potential impact of technological innovations on the UK energy system and Net Zero targets, and help inform decisions on clean energy innovation.

A number of technologies were included as part of the prioritisation but were not included in the systems modelling due to limitations of the models used for the EINAs, data availability and resource constraints. The three hypothetical scenarios developed to represent potential routes to Net Zero were selected due to their differing constraints which provide a more diverse set of outputs and insights.

The technologies and scenarios selected do not represent UK Government policy.

Scale and transformation of innovation

The UK's ambitious Net Zero targets necessitate a fundamental transformation of its energy infrastructure, and as we transition towards a low-carbon economy, the existing energy network faces unprecedented challenges. Significant strides have been made, driven by comprehensive strategies and key publications such as the ‘Net Zero Strategy’ (2021)[1], ‘Delivering a reliable decarbonised power system’ (2023)[2], and ‘Powering Up Britain: The Net Zero Growth Plan’ (2023)[3], which outline progress to date and areas for further action. Recent policy shifts further demonstrate the need to rapidly accelerate network innovation to support future energy systems. The establishment of Great British Energy (backed by £8.3bn

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[1] Net Zero Strategy: Build Back Greener (GOV UK, 2021)
[2] Delivering a reliable decarbonised power system (CCC, 2023)
[3] Powering Up Britain: Net Zero Growth Plan (GOV UK, 2023)

committed funds) and the pulling forward clean power provision by five years to 2030[4] send clearer policy signals to improve investor confidence and market momentum. Ambitions for roughly quadrupling offshore wind capacity (43-50 GW), tripling solar power capacity (45-47 GW), and increasing onshore wind capacity (27-29 GW) will require substantial network investments, where innovation will play a critical role in accelerating transitions[5]. Yet, pathways for achieving these targets remain uncertain, and future energy systems can take various routes. Grid access challenges exacerbate the barriers to deployment. The volume of connection applications to the transmission network has grown ~ ten times since 2021, leading to an average delay of more than five years for projects.[6] Since 2019 (previous EINAs publication), the geographic shift in electricity generation and demand has caused connection delays. This is due to coal asset closures near demand centres, increased renewables at the network edge, industry decarbonisation through electrification, and new power users like data centres closer to the network centre. Innovation that supports transmission and distribution upgrades can play a key role in addressing these grid access issues.

At the transmission level, required change is predicted to be extensive, irrespective of pathway, and the Transmission Acceleration Action Plan[7] acknowledges that the pace of network investment delivered in recent years has been insufficient in the face of Net Zero targets. The newly established National Energy System Operator (NESO)[8] will oversee these significant changes to network transformations. The upcoming Centralised Strategic Network Plan (CSNP) and its periodic three-year planning cycles is a step in the right direction where clear national coordination is needed to bring effective agents of system development around key challenge areas.

The Future Energy Scenarios (FES) framework[9] has evolved to present pathways that highlight strategic choices for GB's energy future, ensuring all meet Net Zero targets. With wind and solar technologies expected to exceed 50% of installed capacity by 2050, transmission reinforcements are crucial. Decarbonisation targets necessitate energy networks to adapt by managing intermittent sources and fluctuating demand while maintaining grid stability. This transformation requires new services for grid stability, increased capacity, and advanced digital technologies. Key determinants shaping these transitions include gas decarbonisation, rapid network electrification, and energy security (Table 1).

The increasing integration of renewable energy sources, coupled with the electrification of transport and heating, demands a robust and adaptable grid capable of meeting the requirements of a decarbonising system. Despite gradual reductions in the CAPEX of critical network technologies, the UK will face rising system costs. The electrification of transport and heating can increase these costs, with peak demand projected to grow by ~15%

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[4] Great British Energy founding statement (GOV UK, Accessed Oct 2024)
[5] Clean Power 2030 Action Plan (GOV UK, Accessed Apr 2025)
[6] Connections Action Plan (DESNZ and Ofgem, 2024)
[7] Electricity networks: transmission acceleration action plan (GOV UK, 2023)
[8] National Energy System Operator (NESO) (NESO, Accessed Oct 2024)
[9] Future Energy Scenarios (FES) (NESO, 2024)

in a high electrification scenario[10]. Stakeholders like Ofgem will need to ensure network transitions are affordable and fair, with RIIO3 price controls[11] guiding innovations for a highly electrified and decarbonised system. Networks are the nexus of the energy system, connecting suppliers, consumers, and technologies, and their role is crucial for achieving Net Zero. However, the pace of change required for Net Zero poses challenges to networks, causing increased constraints.

Table 1: Key fundamental drivers and innovation needs of current UK energy networks

Fundamental driver	Primary network transformation	Primary innovation needs (3)	Counterfactual
Gas network transformation	A decarbonised grid will see a massive transformation of gas networks with variable renewable energy and sustainable fuels filling the void	Stability / reserve provision Gas transformation Sustainable fuel integration	Increased emissions with unmet targets and large system inefficiencies
Electrification of transport and heat	Natural gas and petrol phase-outs will require networks to rapidly change to accommodate new LCTs, primarily in dense urban areas. Constraint-driven evolution will require networks to increase physical capacities, upgrade substations, and flexibly manage system needs.	Transmission / distribution upgrades (enhanced networks, charging infrastructure etc.) Decarbonised heating pathways Automated demand-side response	Heavy fossil fuel dependence during peak demand period in overly constrained systems with economic and innovation lags
Digitalisation and data utilisation	Networks need to continue progression from post-event data operations to real-time and dynamic control through more ubiquitous data streams and system sensing.	Rapid digitalisation of new and existing assets Advanced data analytics and AI Cybersecurity for critical infrastructure.	Less secure, inefficient, and fragmented energy system, unable to meet future demands and Net Zero.

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[10] Future Energy Scenarios: Pathways at a glance (NESO, 2024)
[11] RIIO-3 Sector Specific Methodology Decision for the Gas Distribution, Gas Transmission and Electricity Transmission Sectors (Ofgem, Accessed Oct 2024)

Network innovation should boost economic opportunities, strengthen energy security, and improve supply chains. It must be consumer-centric, accessible, and affordable, supporting dynamic system development. An agile innovation ecosystem is essential to achieve Net Zero goals, adapting to future demands and evolving landscapes that may change funding needs. Core principles guiding innovation priorities in this analysis have centred around:

- Net Zero affordability – Innovation needs to ensure energy affordability for consumers. Whilst achieving Net Zero will require investment, estimated at £10bn/year, net operating savings are projected to outweigh investment costs[12].
- Economic opportunity & industrial strategy – The UK's rapid decarbonisation presents challenges but also creates global export opportunities. Innovative network solutions can enhance the UK's industrial strategy, making it a leader in grid innovation. In 2022-2023, businesses involved in the Net Zero transition contributed £74bn in gross value added (GVA) and offered salaries 23% higher than the UK average[13].
- Resilience and security - Ensuring resilience involves addressing the challenges of capacity expansion, technological advancements, and maintaining reliability amidst changing climate conditions. Secure and reliable energy provision necessitates innovation in both Net Zero supply and demand, as well as crucial supply chains. Onshoring of critical manufacturing and bolstering the security around grid infrastructure supply will bring considerable challenges in strategic growth.
- Optionality - Maintaining optionality involves leveraging innovative solutions to delay significant capital expenditures until there is greater clarity on the decarbonisation pathways of various sectors. This approach allows for flexibility and adaptability, ensuring that investments are made with the most up-to-date information, thereby reducing the risk of stranded assets and optimising resource allocation. With optionality, the UK can better navigate the uncertainties of the energy transition, making informed decisions that align with evolving technological advancements and policy developments.

Responsive innovation pathways are essential to secure a robust system that can connect Net Zero technologies quickly and effectively, potentially surpassing targets with proper investment and planning. Transforming networks to meet future needs requires coordinated efforts towards Net Zero, with strategic investments considering timely interventions and innovation. Balancing system progression involves co-developing various components and technologies to enable sectoral shifts. Identifying critical innovations and understanding system dependencies will create conducive environments for market and network interventions. Network innovation provides significant opportunities for a sustainable, resilient, and affordable energy system. By investing in R&D, fostering collaboration, and embracing innovative technologies, the UK can remain a global leader in the energy transition.

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[12] Fiscal risks report (OBR, 2021)
[13] The UK's net zero economy (ECIU, 2024)

However, the rising costs of grid connection and system integration for renewable energy and low-carbon technologies (LCTs) pose significant challenges.

Previous investment in wider energy system innovation to date has seen ~1,800 electricity projects receive over £1.8bn in funding across the network funding streams (SIF, NIA, NIC etc.)[14]. Gas networks saw a total of £246m to date across the same funding streams. The UK Government's Delivery Plan[15] (2022-25) saw a commitment of £4.2bn in Net Zero research and innovation (R&I), and recent announcements such as ~£22bn for CCUS[16] and ~£1.5bn for the 2024 renewable energy auction round[17] demonstrate continued support for major industrial shifts. Key success stories such as Optimise Prime[18], exemplify the proactive approach towards mitigating the impacts of electric vehicles (EVs) on the electricity distribution network. Similar progress through the Demand Flexibility Service (DFS) represents a significant stride in enhancing electricity supply resilience during peak demand periods[19]. Having a more coordinated strategy would further strengthen the extensive innovation work carried out by UK energy networks. Managing system and stakeholder priorities is challenging, and this fragmentation causes inefficiencies and limited BAU adoption of innovation. It is therefore essential to create a unified framework that encourages collaboration and aligns efforts to drive innovation and transformative solutions.

Integrated approach to meeting future needs

Historically, gas and electricity networks have developed separately, and the future role of gas networks are uncertain, particularly regarding timelines. Reliance on unabated gas must significantly reduce by 2030 and phase out by 2050, but there's uncertainty about fuel substitutes meeting peak demand (across all sectors). Pathways forward must consider decommissioning and repurposing existing infrastructure, as network shifts will affect system resilience and stability. Hurried and uncoordinated policy decisions could delay or derail the UK's transition and an integrated approach, where NESO combines gas and electricity innovation into a cohesive roadmap, is needed. Business models must adapt, as current systems may not suit future coordination. Furthermore, innovation investments should be agile to address uncertainties in future network configurations[20] and plans must involve continuous review, transparency, cross-sector collaboration, and quicker market routes free from administrative burden.

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[14] Energy Networks Innovation Strategy (ENA, 2024)

[15] UK Net Zero Research and Innovation Framework: Delivery Plan 2022 to 2025 (GOV UK, 2023)

[16] Government reignites industrial heartlands 10 days out from the International Investment Summit (GOV UK, Accessed 2024)

[17] Record breaking funding for clean energy in Britain (GOV UK, Accessed 2024)

[18] Optimise Prime (Accessed Nov 2024)

[19] Demand Flexibility Service (NESO, Accessed Nov 2024)

[20] 'Network configurations' refer to the overall composition of future network supply systems. One configuration may be dominated by a rise in offshore wind supply versus another which assumed heavier reliance on hydrogen.

Innovation will require flexibility, optionality, and openness to different pathways to address future network needs, ensuring substantial investments align with investor confidence. The FES pathways (2024) outline various network scenarios, but uncertainties remain in areas like heat and transport electrification and offshore wind connections. Mapping innovation pathways involves addressing five key areas of uncertainty, keeping in mind resource and supply chain constraints:

- Hydrogen: Hydrogen integration and its cost implications, including its production, storage / distribution, remains uncertain due to policy milestones yet to be met [21]. Further details can be found in the Hydrogen EINAs report.
- Demand growth and demand-side (consumer-led) flexibility: The pace of electrification and the potential for demand-side response mechanisms will significantly impact network requirements.
- Natural gas transition: The transition away from natural gas presents challenges for network infrastructure and can heighten risk around grid resilience and stability.
- Carbon neutral and negative technologies: The development and commercialisation of carbon neutral / negative technologies, such as CCS, will influence network infrastructure needs.
- Climate scenarios: Climate change is a fundamental driver to energy transitions and increasing climate pressures will necessitate stronger adaptation measures and resilient network infrastructure.

Changes in uncertainties significantly influence innovation pathways. Recent investments include £2bn in hydrogen electrolysis (2023)[22] and funding boosts for CCUS[16] and demand-side (consumer-led) projects like DFS[23]. Yet, uncertainty in these technologies remains. There are risks in limited progression of system development as highlighted by the FES (2024) pathways which suggest a substantial reduction (~77%) in peak natural gas demand (1-in-20 day) by 2050 if a 'Holistic Transition' is followed (down from 4,593 GWh/day in the ‘Counterfactual’ pathway). Though an important transition fuel, hydrogen adoption faces socio-economic hurdles, including the need for robust and cost-effective hydrogen infrastructure, proving the safety case in all applications, policy on residential heating, general public acceptance, limited use in industrial purposes, and demonstrating value over electrification or biomass. Further details can be found in the Hydrogen EINAs report.

Transitioning the network is made challenging by uncertainty in the deployment of other technologies. The CCC's 2024 report on Net Zero progress,**[24]** recognises that whilst that the UK has met overall targets so far, the rollout of some low carbon technologies (e.g. heat pumps) is slower than expected, bringing significant implications for demand growth and

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[21] Hydrogen Strategy Update to the Market (GOV UK, Accessed Jan 2025)
[22] Major boost for hydrogen as UK unlocks new investment and jobs (GOV UK, Accessed Oct 2024)
[23] 2.2 million sign up to Demand Flexibility Service (NESO, Accessed Oct 2024)
[24] Progress in reducing emissions 2024 Report to Parliament (CCC, 2024)

flexibility of the network. There is also uncertainty regarding the extent of demand growth from hyperscale data centres, which are increasingly powering AI models. Manufacturing bodies are calling for clearer policies, as seen in the Electrify Industry report (2024)[25], which urges better business models for hydrogen production and CCUS. These sectors show both progress and challenges, with opportunities for growth and innovation. Major network sectors like fusion and nuclear (SMRs), significantly alter decarbonisation pathways and innovative business models may emerge to support this growth, such as private wires, co-located renewables, iDNOs, and microgrids.

Given the very dynamic nature of system development, innovation will need to sit alongside coordinated efforts to continuously feed research, network needs, and learnings into planning. It will need to include optionality around non-technocentric innovation needs (workforce, commercial, legal etc.) as networks accommodate rapid changes in technologies, demand, and decarbonisation. Further to this, optionality and openness in innovation demands an approach of funding ‘strategic failures'. Here, public funding not only buoys markets in need of intervention but also influences immature markets where progression to Net Zero is unclear, yet crucial. While innovation pathways should continuously, and efficiently, morph to suit wider system needs, an adaptable and robust innovation framework provides clarity to network agents to provide confidence in their approach.

Strategic coordination required in innovation

Well-coordinated innovation frameworks with clear direction and leadership are vital to progress in network transitions. Innovation would benefit from increased coordination across the sector and more strategic direction setting, where ownership and buy-in is equitably sought amongst key stakeholders. Wider energy policy decisions, network priorities and interests, innovation in business, legal, and financial models, all need a holistic alignment in guiding innovation pathways. The Smarter Grid Forum in the UK – a collaborative initiative established by the then Department of Energy and Climate Change (DECC) and Ofgem[26] – presents a good example of successful past cross-organisational cooperation. System level innovation would benefit from a similarly aligned and joined-up approach. The benefits of a well-coordinated and cohesive approach to innovation are very significant, particularly in an environment where accelerated transitions are required. R&I/D and network investment learnings can also be lifted from key international case studies and reports such as the Department of Energy’s Pathways to Commercial Lift-off report in the United States[27] that outline critical network technology investments.

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[25] Electrify Industry Report (Make UK, Accessed Oct 2024)
[26] DECC and Ofgem Smart Grid Forum (SGF) (Ofgem, 2024)
[27] Pathways to Commercial Liftoff: Innovative Grid Deployment (US Department of Energy, 2024)

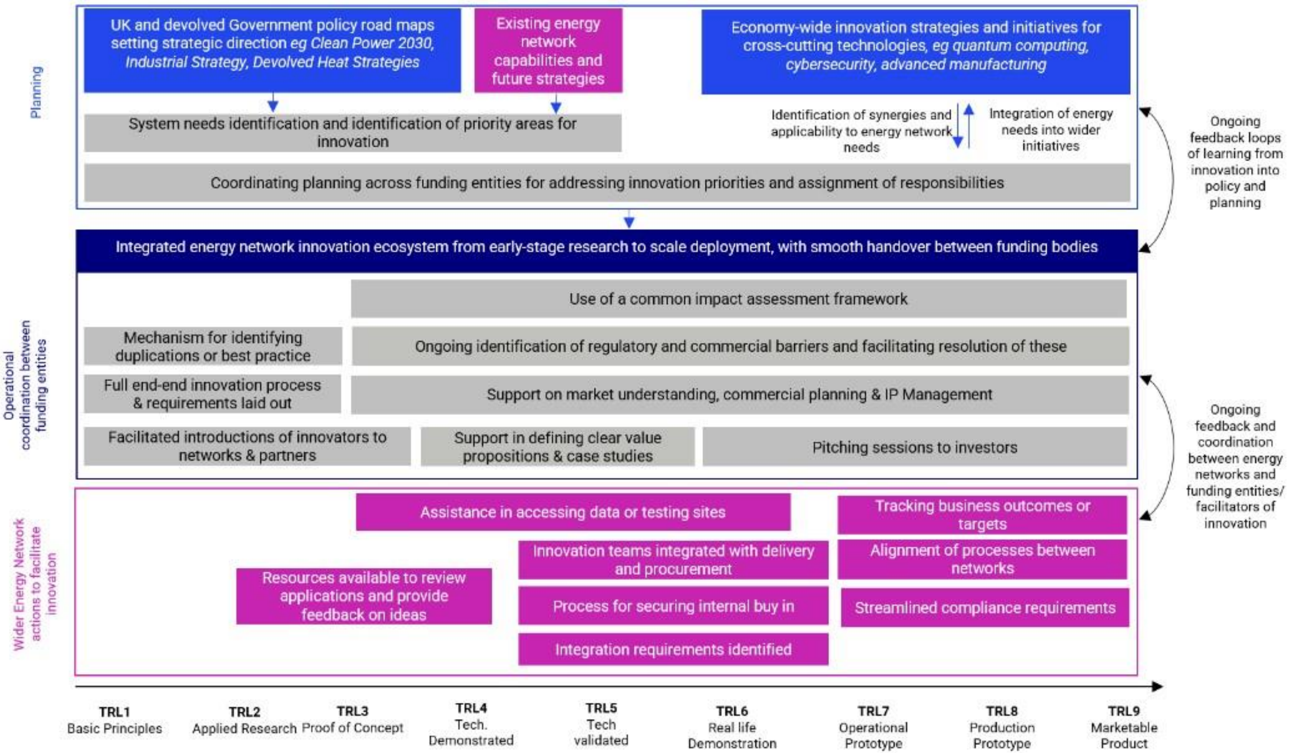

Figure 1: Conceptual energy network innovation ecosystem.

This report is intended to aid in developing foundations for strategic coordination. There is no overarching innovation roadmap for actors to coordinate around and multiple dissemination points (university early-stage research, DNO/GDN strategies, ENA innovation strategy, Ofgem / SIF innovation strategy etc.) need to be ‘pulled up’ into strategic and periodically published energy sector ‘manifestos’. Progressing findings will require coordination between Ofgem, DESNZ, IUK, and other key stakeholders such as the ENA and Future Energy Networks (IGEM) for innovation that is coherently communicated in plans, policy, and investment streams, shown in Figure 1.

Prioritisation methodology

Key Chapter takeaways

- This report focuses on innovation needs within specific networks, following the EINAs programme. It aligns with other sector reports for coherence.
- The prioritisation framework (Figure 2) comprises three phases. It narrows down from 12 network technology areas to those technologies crucial for achieving Net Zero targets and requiring public funding.
- Findings are not absolute, and this report represents an innovation framework that can be used in an agile manner to assess and prioritise innovation across network technologies.

EINAs programme covers various energy sectors and is detailed in the EINAs Methodology Report. Although this report uses a modified methodology, our prioritisation aligns with the EINAs approach, incorporating insights from the UK TIMES and highRES modelling. Each sector report in the EINAs programme considers energy network interactions and considerations, highlighted as significant enabler in LCT deployment and decarbonisation of industry and heating. We used the EINAs prioritisation framework for our high-level sectoral analysis (covering power systems, hydrogen, industry, nuclear, etc.), focusing on 12 key network technology areas (Table 2; see Appendix A.2 for details). While some technology areas like heat, storage, and hydrogen are covered in other EINAs reports, fundamental innovation drivers have influenced our findings.

The energy networks' needs and priorities have been guided by the Technical Expert Group (TEG), which includes key innovation and technical expertise from electricity and gas networks. The TEG's integrated approach involved input from Distribution and Transmission Network Operators (D/TNOs), National Energy System Operator (NESO), the ENA, academic advisors, and entities such as the Energy Systems Catapult and Power Networks Demonstration Centre (PNDC). DESNZ, Ofgem, and Innovate UK were also significant stakeholders. Workshops with the TEG allowed for open discussions on network priorities. Initial TEG engagements[28] focused on 12 key technology areas, resulting in five prioritised network outcomes (Table 2) validated through stakeholder engagements. Over five months, academics and industry experts helped validate these outcomes and identify critical technologies needing public funding to achieve Net Zero targets

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[28] Feedback was garnered from a wide and diverse range of stakeholder representation (networks, innovators, academics, investors, policy makers etc.). Please note that specific expert names have been excluded.

Table 2: Prioritisation of technology areas into five distinct network outcomes (all encompassing both electricity and gas networks).

Green denotes technology areas seen as high priority by the Technical Expert Group (TEG).

Innovation Categorisation	Technology areas	Prioritisation	Network Outcomes
Key infrastructure	Enhanced network capacity	🟩	Enhanced network capacity
	Power electronics (transmission / distribution)	🟥	
	Applied technologies	🟥	
	Eco-designed infrastructure	🟥	
	Grid forming technologies	🟥	
Digital Processes	Control systems and digitalisation	🟩	Digitalised control systems and 'smart' networks
	Data analytics	🟩	Digitalised control systems and 'smart' networks
	Process-based innovation	🟥	
General Network Innovation	Cybersecurity and cyber-physical systems	🟩	Cybersecure networks
	Integrated energy systems	🟥	
	System resilience	🟩	Resilient and climate-ready networks
	Supply chains	🟩	Sustainable and secure supply chains

Note: Climate resilience was added to System Resilience in prioritisation; LDES was included by networks but covered in wider EINAs; Integrated energy systems seen as core theme and covered throughout the report; Aspects of lower priority areas are interspersed throughout the report.

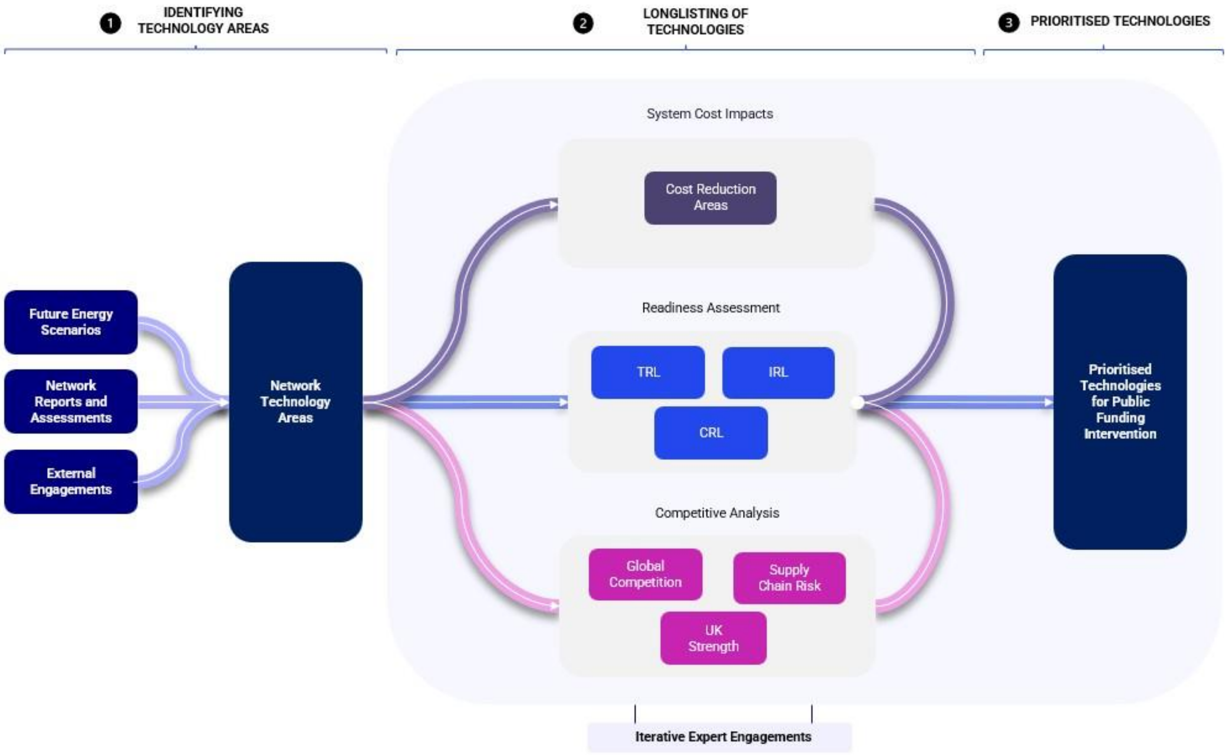

Figure 2: Prioritisation framework used to refine technologies critical for public funding intervention in meeting Net Zero.

As with the other technologies explored in the EINAs reports, innovation needs were prioritised by the core EINAs programme metrics of Net Zero criticality (UK relevant), energy security, technology readiness (technology, commercial, integration), suitability of public funding intervention. The overall prioritisation framework used in our analysis is summarised in Figure 2 and it is important to note that all stakeholder engagements were contextualised around plausible future energy systems. The framework moved across three main stages of establishing key technology areas (1), longlisted technologies (2), and finally, prioritised technologies (3). Each technology (established from engagements and secondary research) was assessed against system costs impacts (alleviating constraints, reducing fixed operating costs etc.), and consumer interests were at the core where affordable, accessible, and equitable energy provision guided prioritisations to ensure a consumer-centric approach.

Innovation timelines are crucial for successful funding interventions, as discussed in the next section. Therefore, an analysis of current technology, commercial, and integration readiness levels complemented the list of specific technologies. This filtering is essential for determining suitable innovation pathways for public funding. For example, prioritised network technologies highlights quantum computing and quantum encryption / cryptography as key technologies for developing a cybersecure energy future. Quantum encryption / cryptography, identified as high-priority due to recent advancements, is well-suited for public funding, however, quantum computing's impact on network operations is very unlikely to meet 2050 innovation needs, leading to its deprioritisation at this time.

A further assessment of competitive advantage for high-priority technologies was conducted to identify where UK markets can excel domestically. This evaluation also considered supply chain risks to gauge overall UK strength in these technologies. The full assessment has indicated prioritising of technologies (*High*, *Medium*, *Lower*) based on their importance in achieving Net Zero by 2050. Technologies that enable rapid network development supporting Net Zero targets were prioritised, acknowledging necessary system transformations. Electricity systems received significant focus, but gas networks remain crucial despite uncertainties, and while many gas network needs fall under price control options (RIIO-Gas Distribution), an integrated system analysis was emphasised for effective innovation pathways with public funding.

Three of these high-priority technologies are presented in further detail in the technology deep dives section where their deployment from 2025 up to 2050 (5-year intervals) was used to input data to business opportunities calculators for an assessment of Gross Value Added (GVA), job creation, and UK market share. The deep dives were guided by technology appropriateness (some lacked enough specificity for modelling rates and scale of deployment, e.g., ‘Critical AI tools for networks’), data availability, and confidence of assessment / modelling. More details on the overall methodology used with the business opportunities calculators can be found in the EINAs Methodology Report.

There are key uncertainties and data / modelling limitations that sit alongside the outlined prioritisation framework, and any shortlisted technologies must be viewed within these boundaries, particularly with the acknowledgement that agile innovation pathways will present new options in our rapidly evolving energy system. While techno-centric in scope, there are many non-technical elements that enable and influence network evolution and this report will present necessary shifts in business models, crucial step changes required to unlock system transformation, and important barriers to overcome (resources, supply chains, planning etc.).

Findings in this report are not absolute and do not represent the views of government. While results and prioritised technologies were validated through further engagement with the TEG, the report is a means to provoke further conversation and development of viable pathways across energy sectors.

Prioritised network technologies

Key Chapter takeaways

- Findings present eleven (11) *high*-priority technologies suitable for public funding intervention, where innovation will bring substantial impact for meeting Net Zero.
- Innovation will be important across various technologies. *Medium* and *Lower* prioritised technologies are largely enabling technologies for wider system development.
- Technologies that provided enhanced network capacity featured heavily (5) in shortlisted eleven (11) technologies, those falling in digital and control system innovation (22) represented approximately a third of technologies across *Medium* and *Lower* prioritisations.
- Innovation needs extend beyond technological advancements and network evolution will require fundamental shifts in business models, planning processes, and legal and financial frameworks.

Overview of prioritisations

A total of 64 technology areas were assessed in our analysis against the five network outcomes – some having much more specificity in required technologies (e.g., Dynamic Line Rating, DLR) whereas others represented a ‘technology family’ (e.g., critical AI tools for networks). Of this longlist, separation was made by *Medium* (19), *Lower* (21) prioritisations with a further 13 technology areas falling out of scope in our analysis owing to coverage in other EINAs sector reports (See table 3). Although technologies that provided enhanced network capacity featured heavily in shortlisted technologies, those falling in digital and control system innovation (22) represented approximately a third of technologies across *Medium* and *Lower* prioritisations.

Table 3: Breakdown of prioritised network technology areas (complete assessment set)

		Enhanced network capacity	Digitalised control systems and ‘smart’ networks	Cybersecure networks	Resilient and climate-ready networks	Sustainable and secure supply chains	
Count	High	5	2	2	2	0	11
	Medium	4	7	2	2	4	19
	Lower	6	10	2	3		21
	Out of Scope	6	3	-	4	-	13
	Total	21	22	6	11	4	64

Table 4: High-priority technologies / network innovation areas with primary innovation needs / gaps.

Note: Three main innovation categories (ordered, highest priority of 1) are shown: T (technological advancements that directly improve readiness levels); C (commercialisation for greater adoption and deployment); I (primarily large-scale demonstration on live systems). Relative innovation priorities (bar level) are shown. Technologies are split across the five network outcomes of Enhanced network capacity (1), Digitalised control systems and ‘smart’ networks (2), Cybersecure networks (3), Resilient and climate-ready networks (4). See Appendix A.3. for an expanded version of this table.

	Technology area	T	C	I	Primary innovation needs
1	Second-generation cables	2	1	3	Large cost reductions in second-generation cables, focused primarily on high temperature superconducting cables in this work (HTS), wire and tape needed for improved commercial case in network application. This is compounded by R&D need for better fault mitigation and recovery
	HVDC converter hubs	1	3	2	Centralising HVDC connection points needs greater testing and simulations of system configurations to stay ahead of needed tech. spec, planning, and grid code developments for the oncoming offshore boom.

	Distributed feeder technologies	2	3	1	Innovation primarily lies in understanding optimal system topologies to meet project reinforcement demands, as well as advances in greater feeder sensing and automation.
	Dynamic Line Rating (DLR)	2	3	1	While at a high TRL, DLR innovation is needed for wider system integration with full suite of network monitoring technologies for more holistic and real-time line sensing.
	Subsea cabling	1	2	3	Innovation is required to increase power, decrease losses, and increase their maximum subsea depth while retaining commercial viability.
2	Advanced next-generation dispatch algorithms	2	3	1	As with DLR, control and dispatch innovation requires the ability to process vast amounts of data from various sources (smart meters, weather forecasts, grid sensors etc.), to optimise energy dispatch in real-time
	Critical AI tools for networks	2	3	1	AI usage in networks has been around largely for post-processing and while many AI applications exist, large gains from AI advances can be made in network planning, system coordination (flexibility scheduling etc.) and asset optimisation.
3	Quantum encryption and cryptography	1	3	2	Key innovation lies in the development and implementation of quantum-resistant cryptographic algorithms to 'beat the curve'. These need further innovation to ensure that network data remains secure in the future, even as quantum computing technology advances.
	Islanded architecture of critical infrastructure	2	3	1	Demonstration on existing network assets remains untrialled. Need to implement technologies for real-time data on system performance and enable dynamic adjustments to maintain stability and efficiency.
4	Grid-forming technologies	2	3	1	Optimal penetration of grid-forming inverter-based resources (IBRs) vs grid-following IBRs, as well as live system trials to determine the wider system impacts when integrated.

Gas network repurposing	Innovation primarily lies in the operational and business models needed for a coordinated and integrated system approach to decarbonisation of gas assets by 2050.

Following the prioritisation framework shown in figure 2, eleven (11) technology areas were identified as high-priority for public funding. Table 4 presents these technology areas and the primary innovation needs of each. It is important to stress that a) the exclusion of a specific technology does not indicate a lack of importance, and b) much-needed areas of innovation are included in our full prioritisation (Appendix 2) but were deemed as less critical in innovation need towards Net Zero. The scope of public funding activity focused our analysis on specific areas of limited market momentum / failure, and areas of strategic growth and investment for the UK. There are many important technologies that are not shortlisted as there is significant market momentum currently.

Technology areas in Table 4 are in no particular order of priority, however, second-generation cables, DLR, and distributed feeder technologies were chosen for 'deep dives' where deployment and economic modelling provide more insights (see Technology Deep Dive section section). Other high-priority technologies are discussed in this section, presenting key economic and innovation findings. The following overview sections will expand on the high-priority technologies in each of the network outcome areas.

Outcome-specific findings

Enhanced Network Capacity (electricity transmission)

Key takeaway: Accelerating innovation in transmission technologies is critical *to expand network capacity, integrate offshore renewables, and ensure scalable, cost-efficient grid development through standardisation and interoperability.*

Barring distributed feeder technologies (dynamic technologies for substation management), the most critical innovation needs lie within transmission technology areas that provide enhanced network capacity. Transmission networks are expected to operate at much larger capacity and distribute energy more efficiently in a rapidly decarbonised system being fuelled by a greater diversity of low-carbon sources. The highly probable and considerable expansion of offshore wind, the accelerated deployment of LCTs and EVs, the implications of which are already being seen through the current constraints in the network, are all key drivers.

Furthermore, given the continued investment in offshore technologies, and continental and domestic subsea transmission[29], innovation around high-voltage direct current (HVDC) converter stations and their integration with AC systems is critical for connecting future network assets. The UK is leading HVDC innovation through projects like Project Aquila[30] but needs to remain competitive through continued development of 'HVDC converter hubs' where various technologies can be tested in 'plug-and-play' sandbox environments to determine optimal configurations and architectures on a simulated live system. To develop HVDC converter hubs effectively, several key steps must be taken to ensure cost efficiency and rapid rollout. Firstly, enabling competition among vendors will help drive down costs and increase availability of components at the specification required. Increasing the number of manufacturers producing gas insulator switch gears at the required specifications will also support the scalability of HVDC infrastructure. Additionally, introducing commercial metering at HVDC connection points is necessary, but this requires the development and testing of specification. To accelerate deployment, interoperability of standardised cables must be prioritised to prevent purchase order delays. Collaboration with the wind industry is essential to improve load rejection response times, which can be achieved through industry consultations, changes in grid codes, and innovation projects. Clearer grid regulations should be established to ensure all stakeholders understand system-wide solutions. Lastly, investments strategies must be structured to guarantee that early-stage planning aligns with future development needs, ensuring sustainable and scalable development of HVDC converter hubs.

Furthermore, extra high-voltage direct current (EHVDC) innovation, specifically in technological advancements that improve commercialisation and deployment rates, is a much-needed area of investment as UK networks diversify transmission routes. EHVDC cabling innovation present opportunities for onshoring critical manufacturing and while recent advancements[31] demonstrate moves towards greater UK market shares, further potential exists. Alternative transmission solutions have been proposed, driven by academic research. Low Frequency AC (LFAC), an adaptation of HVAC transmission that operates at a lower frequency of 16.7Hz, offers the advantage of eliminating the need for an offshore converter station, compared to HVDC[32]. Additionally, LFAC shares HVDC's low reactive power compensation requirement but benefits from simpler cable manufacturing using polar insulation materials.

Digitalised control systems and 'smart' networks

Key takeaway: Implementation gaps remain in *non-techno-specific processes (e.g. skills, data scaling, investment costs), with* innovation *and public support needs* in *control system optimisation and AI use in network management.*

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[29] Groundbreaking ceremony marks start of construction on £4.3bn electricity superhighway between Scotland and England (National Grid Group, 2024)

[30] Aquila Interoperability Package (The National HVDC Centre, Accessed Oct 2024)

[31] Ayrshire cable plant to create 900 manufacturing jobs (The Herald, 2024)

[32] Low Frequency AC transmission for offshore wind power (Renewable and Sustainable Energy Reviews, Accessed April 2025)

Energy network digitalisation has been well-documented as a key investment area towards Net Zero, with multiple benefits and strategies being outlined in key reports such as the Energy Digitalisation Taskforce[33], and DNO publications[34].While an understanding of digital revolutions are understood in the network innovation space, implementation gaps primarily lie across non-techno-specific processes (skilled and adequately staffed workforces, scaling data systems, high investment costs) as TRLs are sufficiently high in a wide range of technologies. Furthermore, advancements in digital innovations lie within Ofgem RIIO price controls[35], with RIIO-3 regulating in a similar fashion. This is seen across both electricity and gas networks, distribution, and transmission. Public funding does play key roles in innovation in non-network assets however, with the NZIP having funded important areas such as interoperability (£9.15M) and flexibility asset registration (£2M) for distributed and demand-side assets[36], supporting greater scale up of critical technologies on operational networks.

Where digital testbeds can go further primarily lies in control system optimisation, and the role of AI in network management and optimisation. While projects such as ENSIGN[37] and Crowdflex[38] are demonstrating key learnings across digital twin innovation and control room operation, AI implementation is largely poorly understood, particularly from a risk perspective in a very regulated environment where consumer and energy security are paramount. This innovation gap presents a strong opportunity for public funding. While AI R&D is not at risk of falling behind, network investments and trials will likely suffer without urgent and accelerated action. This is especially true given that policy and regulatory environments are not keeping pace with technological advancements [39], [40].

Many routes of network digital innovation are already being explored, and gaps are seen in more advanced and automated control systems for real-time sensing, monitoring, and control. Implementing real-time monitoring systems combined with advanced analytics will provide better visibility over energy flows. Room for accelerated innovation also exists at key transmission and distribution (primarily electricity) nodes for automated power flow and grid-edge decision-making under varying system conditions (tightness, extreme events, fault management). These changes should be underpinned by secure and efficient data sharing infrastructure to facilitate seamless data exchange between energy system agents.

Cybersecure networks

Key takeaway: Cybersecurity *is a well-established concern for networks* but there is a lack of

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[33] Energy Digitalisation Taskforce publishes recommendations for a digitalised Net Zero energy system (Energy Systems Catapult, Accessed Oct 2024)

[34] SGN Digitalisation Strategy (SGN, 2020)

[35] Network price controls 2021-2028 (RIIO-2) (Ofgem, Accessed Oct 2024)

[36] Energy Digitalisation Taskforce report (GOV UK, 2022)

[37] SP Energy Networks leads the way with trailblazing AI-led 'digital twin' that will change the future of the UK energy industry (SP Energy Networks, 2023)

[38] Crowdflex (NESO, Accessed Oct 2024)

[39] AI risks for energy networks: challenges, management and regulation (Energy Systems Catapult, Accessed Oct 2024)

[40] Artificial Intelligence (AI) within the energy sector (Ofgem, Accessed Oct 2024)

clear direction, with innovation *needs in AI cybersecurity, quantum-safe technologies and resilience measures such as islanding critical infrastructure.*

Expert engagements, validated in published literature and report, confidently place cybersecurity in networks as a top priority area for innovation. However, limited workforce capacity, lower TRL technology options, and nascent strategy in collective network direction and policy create stagnation where innovation is concerned. Whilst networks accept this priority area for innovation, there is a lack of understanding of the key technologies, and insufficient processes and systems to implement. Even where technology advancements have entered more 'live' demonstrations, such as in some quantum-safe technologies, progress is almost solely being led by large research centres and non-network corporations, with little to no innovation feeding learnings and systems into network operations (ample opportunity exists for the cross-sector collaborations to address high-priority risks). Related to the previous technology area, cybersecurity considerations for using AI in networks should be a focus of innovation pathways.

In such a critical aspect of network ecosystems, substantial risks exist in falling behind major powers such as China, and some infrastructure vulnerabilities are already raising concerns[41, 42]. Energy networks are not alone in these threats and innovation infusions from other critical sectors such as communications and national IT systems can push networks closer to realising clear strategies. 'Islanding' critical national infrastructure (CNI) (HVDC converters, data centres, control rooms etc.) is another high-priority recommendation where a suite of technologies is already being employed in other sectors and can build resilience and energy security across networks. The establishment of the Cyber Security Working Group[43] along with recent announcements, such as data centres being classed as CNI[44], are positive steps forward.

Resilient and climate-ready networks

Key takeaway: System and climate resilience, while high-priority network outcome states, do not present clear innovation pathways. Flexible funding and collaborative approaches are needed to repurpose gas assets, integrate low-carbon fuels like biomethane, and address uncertainties in future network configurations.

Despite the critical importance of resilience in energy networks, the pathways for innovation are not as clearly defined as in other areas which have been identified as a priority network outcome. Technologies such as grid-forming control (inverter-based resource) can play enabling roles for larger decarbonisation efforts as more variable renewables penetrate the grid[45]. Their function in providing synthetic inertia to the system enhance the stability and resilience of the electricity grid as the UK transitions to a low-carbon

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[41] Britain's National Grid drops China-based supplier over cyber security fears (Reuters, 2023)

[42] NCSC warns of enduring and significant threat to UK's critical infrastructure (NCSC, 2024)

[43] Cyber security – Energy Networks Association (ENA, Accessed Oct 2024)

[44] Data centres to be given massive boost and protections from cyber criminals and IT blackouts (GOV UK, 2024)

[45] Grid-Forming Technology in Energy Systems Integration (ESIG, 2022)

energy system. Key innovation projects such as INCENTIVE (SIF)[46] demonstrate strategic value of these systems, but live system integration is needed before full benefits are realised – also true for understanding the necessary grid and policy reforms. Hornsea 4 is expected to be Europe’s first offshore wind to install an Enhanced STATCOM, as investigated in INCENTIVE. A Commercial Operation Date has been announced for 2030. Additionally, initiatives like the Climate Resilience Demonstrator (CreDo) and subsequent CreDo+[47], highlight how integrated data can improve decision-making and operational coordination, ultimately bolstering network resilience. However, these findings present innovation shifts in operational and system design versus specific technology prioritisations.

The broad and interconnected nature of system and climate resilience makes it overall difficult to pinpoint specific technologies that would most benefit from public funding. This uncertainty necessitates a more flexible and adaptive approach to funding, focusing on a wide range of potential innovations rather than a narrow set of predefined solutions. Consequently, while resilience remains a high-priority outcome, the lack of clear innovation pathways reduces the confidence in specific technology prioritisations, evidenced by only one in six longlisted technologies falling in this category. Furthermore, future network configurations are unclear and bring uncertainty to resilience where the role of gas, in increasingly electrified networks, is concerned.

Globally, projections show, in the context of keeping global warming below 2°C targets, that natural gas will have a significantly limited role in 2050 energy mixes[48]. However, as the UK presses ahead to achieve its Net Zero targets, the future of natural gas in domestic networks remains uncertain due to the increasing emphasis on variable renewable energy sources, lack of clear hydrogen-specific policy, and barriers to large-scale battery and LDES solutions / deployment.

Significant changes in the gas infrastructure are needed, and this transition necessitates a collaborative approach involving various stakeholders, including DNOs, water utilities, and communication providers etc., to develop strategic plans for repurposing gas network assets, at a regional scale. Challenges such as decarbonising multioccupancy buildings, gas-electricity interfacing in buildings, and the phase-out of gas networks in operational areas, are some of the areas in need of coordinated approaches given the sizeable impact innovation in this space can have.

Ensuring an effective decarbonisation (including decommissioning) of gas networks will need key step changes in innovation with sequential, yet interrelated, innovation in low-carbon alternate fuels, gas network repurposing, and finally, strategic decommissioning (domestic and hard-to-abate assets) after other pathways have been assessed. While advancements in hydrogen production, carbon capture, utilisation, and storage (CCUS), heat, and storage are covered in other EINAs sector reports, our analysis suggests that public funding investments in

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[46] INCENTIVE - Innovative Control and Energy Storage for Ancillary Services in Offshore Wind (ENA Innovation Portal)

[47] CReDo (Accessed Nov 2024)

[48] Deloitte Sustainability and Climate: Natural Gas Demand Outlook to 2050 (Deloitte, 2023)

biogas (biomethane in particular) may prove beneficial as alternative fuels fills gaps in the decarbonisation journey – as the right market incentives and financial mechanisms to drive the innovation are currently limited, aside from the Green Gas Support Scheme[49].

Opening innovation in gas networks will allow faster decarbonisation through strategic cross-sector collaborations in decommissioning and repurposing gas assets. By leveraging learnings paired with shared innovation needs, a collaborative and integrated systems approach will open multiple pathways and options for asset repurposing. While findings show that the majority of gas network operation innovation needs (asset and operational digitalisation, leak detection etc.) fall within price controls set by Ofgem RIIO2[50], asset repurposing and decommissioning need public funding. Although many projects have explored the repurposing of gas networks for future use such as hydrogen blending or biomethane integration[51, 52, 53], coordinated efforts are required to ensure compatibility, efficiency, and strategic pathways. Biomethane in particular shows promise as a low-carbon fuel for wider network use but innovation in this sector must focus on improving the efficiency, scalability, and economic feasibility of biomethane production and distribution. Specifically, innovation gaps lie in upgraded production, injection infrastructure and smart gas network technologies to ensure stability and reliability, and regulatory frameworks to support producers while addressing key market barriers (grid compatibility, commercialisation etc.) Some key market barriers identified include the challenge of reverse compression for pushing up pressure tiers to facilitate supply-demand matching, managing seasonal injection volumes to account for variations, accurately measuring mixed gases to ensure proper accounting and quality control, and the complexities involved in distributed storage of biomethane across various locations[54, 55]. These areas are where public funding can support large risk environments where there is currently network inertia. Projects such as RESOP (Regional Energy System Optimisation Panning)[56] are positive steps to leveraging a whole system approach.

By fostering a collaborative environment and leveraging public funding, the UK can effectively navigate the uncertainties surrounding the future of gas networks and ensure a smooth transition towards a decarbonised energy system.

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[49] Green Gas Support Scheme (GGSS): open to applications (GOV UK, Accessed on Oct 2024)
[50] Network price controls 2021-2028 (RIIO-2) (Ofgem, Accessed Oct 2024)
[51] FutureGrid Phase 1 – 5% Hydrogen Blend Test (ENA Innovation Portal)
[52] HyCoRe (ENA Innovation Portal)
[53] Gas Goes Green project to explore how biomethane could work alongside hydrogen to accelerate net zero efforts (Wales & West Utilities, Accessed Oct 2024)
[54] Bioenergy, biogas, and biofuels: Research and innovation gaps in the EU (EERA Bioenergy, 2024)
[55] Innovative technologies for biomethane production (BIP Europe, 2023)
[56] Regional Energy System Optimisation Planning (RESOP) (ENA Innovation Portal)

Barriers to progress

The path to widespread deployment of high-priority technologies is challenged by several barriers, ranging from technical challenges to policy and regulatory hurdles. Table 5 outlines these technologies and details the key barriers (ordered) that need to be addressed to enable their successful integration and adoption within the energy networks. This information is further complemented with the overall system value that is achieved through public funding to unlock accelerated network innovation.

Common barriers across many technologies include strong cases for further commercialisation through R&D (e.g., second-generation cables, quantum encryption), integration with existing infrastructure (e.g., distributed feeder technologies, advanced dispatch algorithms), and regulatory challenges (e.g., grid forming technologies). These barriers present roadblocks to widespread adoption and effective deployment and some technologies, such as superconducting cables and HVDC converter hubs, face additional unique barriers like technical standards, cooling system reliability, and key supply chain risks. Addressing these obstacles involves developing cost-effective materials, creating industry-wide standards, enhancing system efficiency, and incentivising new suppliers.

The overall system value gained from overcoming these barriers is significant and there is roughly an even spilt in the technologies needing stronger focus in R&D developments for further commercialisation, and those with mature enough TRLs where demonstrating key system integration is critical. Enhanced network capacity, particularly in urban areas, supports an uplift of local renewable energy integration while improving grid stability and operations. Optimised transmission monitoring and automated distribution management through DLR, advanced dispatch algorithms, and distributed feeder technologies will have wider system implications, particularly for peak management and unlocking further connections in previous constrained zones. Addressing some barriers plays a strategic role in futureproofing the system against cybersecurity threats, and embedding further resilience, as seen through innovation in quantum encryption. Public funding to support high innovation not only supports the UK in meeting its Net Zero targets by 2030 and 2050 but also enhances the overall resilience, reliability, and efficiency of networks.

Table 5: Barrier summary (ordered by priority) of high-priority technologies / network innovation areas with key system solvers and value presented (ordered).

Note: An indication of the current state of the technology areas is highlighted through the main classifications of their current innovation phases, 'Learning by R&D' (where technological and commercial constraints are primary barriers, 🟧) and 'Learning by doing' (where wider system integration and demonstration are primary barriers, 🟦). Technologies are split across the five network outcomes of Enhanced network capacity (1), Digitalised control systems and 'smart' networks (2), Cybersecure networks (3), Resilient and climate-ready networks (4), and Sustainable and secure supply chains (5).

	Technology area	Current barriers	System solvers	System value unlocked
1	Second-generation cables	High cost of materials and installation Lack of technical standards Cooling system reliability	Develop cost-effective HTS wires and tapes Create industry-wide technical standards (e.g. fault control) Enhance cooling system efficiency and reliability	Enhanced network capacity, particularly for managing constrained urban connections, easing connections burden
	HVDC converter hubs	Technical interoperability Limited supplier competition High capital costs	Continue to innovate and adopt multi-vendor interoperability standards / configurations Incentivise new suppliers and onshoring Commercialisation through optimal system configurations	UK remains competitive globally in this space, accelerating the pace of offshore wind deployment in particular
	Distributed feeder technologies	Integration with existing infrastructure Regulatory challenges Potential supply chain risks	Demonstrations in highly constrained nodes Implement supportive regulatory policies Coordinate system and spatial planning for efficient deployment	Accelerated decentralised energy generation, enhanced local energy reliability, and the meeting of projected reinforcement demands. These technologies offer large opportunities from unlocking great EV and heat pump deployment.
	Dynamic Line Rating (DLR)	Data integration challenges Accuracy and reliability	Create robust data integration platforms Advance R&D in data processing algorithms	Optimised infrastructure monitoring and management will lead to real-time grid management, and increases transmission capacity during peak

		Regulatory acceptance	Establish regulatory frameworks for DLR adoption	demand, unlocking further renewables integration
	Subsea cabling	Further commercialisation Installation complexity High maintenance costs No HVDC cable supplier / OEM in UK	R&D for further cost-reductions Innovate in modular and scalable installation techniques Implement predictive maintenance technologies	Accelerates offshore wind integration, interconnects more EU energy markets, and supports reliable long-distance power transmission within the UK
2	Advanced next-generation dispatch algorithms	Integration with legacy systems Input data accuracy Market incentives	Develop hybrid systems for seamless integration Live demonstrations to quantify risks Reduce risk through incremental scaling	Key gains made in more efficient dispatch, particularly in an ever complex and variable system with various temporal and spatial needs. Enhances renewable energy utilisation and grid balancing
	Critical AI tools for networks	Algorithm transparency Data trust and availability Cybersecurity risks	Develop transparent and explainable AI models with clear decision outputs Implement robust data governance frameworks Enhance cybersecurity measures and protocols	Significant system gains can be made in predictive maintenance, network forecasting grid reliability through balancing, and reduced reinforcement pressures
3	Quantum encryption and cryptography	High R&D costs Technical complexity Standardisation	Fund strategic interventions for cost-effective quantum technologies Simplify deployment processes through agile approach	Protects critical infrastructure from cyber threats, ensures secure communication in smart grids, and supports data integrity

			Establish industry standards for quantum encryption	
	Islanded architecture of critical infrastructure	Technical integration High setup costs Regulatory hurdles	Innovate in ‘quick win’ integration technologies De-risk through funding interventions Implement supportive regulatory policies	Ensures continuous operation of critical services during grid disturbances, supports microgrid development, and enhances resilience against hacks and cyberattacks
4	Grid-forming technologies	Live system technical validation Regulatory alignment Further commercialisation	Conduct pilot projects for validation Establish regulatory frameworks and grid code reviews for deployment Develop cost-sharing initiatives	Enables higher penetration of renewable energy sources, particularly offshore wind through improved system inertia and grid stability
5	Gas network repurposing	Fragmented coordination Infrastructure compatibility with alternate uses (fuels, cabling etc.) Regulatory barriers	Strategic coordination across utilities and private sector Comprehensive spatial planning and mapping of assets Reform regulatory policies to encourage repurposing	Facilitates the use low-carbon gases, while decarbonising existing networks through asset repurposing and decommissioning

Critical innovation pathways of high-priority technologies

Investing at the right time is essential to ensuring funding effectiveness. Innovation in immature market and technology ecosystems can result in lowered benefit potential through public investments due to limited market offtake at time of delivery. For instance, while the funding of early V2G projects[57, 58, 59] in the UK illustrated that V2G technology has significant

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[57] My Electric Avenue (Project site, Accessed Oct 2024)
[58] Case study (UK): Electric vehicle-to-grid (V2G) charging (Ofgem, Accessed Oct 2024)
[59] £30 million investment in revolutionary V2G technologies (GOV UK, Accessed Oct 2024)

benefits and potential, significant market, policy, and regulatory barriers needed to be addressed at the time before projects could lead to widespread adoption.

Figure 3 outlines the innovation pathways and timelines for shortlisted technologies essential for the meeting Net Zero targets (2030, 2050) based on likely future network configurations. The objective of innovation in this context is to accelerate progression towards commercial deployment, and these are indicative timelines which could be targeted for acceleration, however, ones that can only be achieved through strategic management of wider policy and system barriers.

Findings highlight the urgency and feasibility of innovation in these areas, emphasising the need for targeted interventions to ensure the UK meets its ambitious goals. Using the baseline (2024) technical, commercial, and integration readiness levels (left), the diagram outlines the indicative timelines (based on primary and secondary analysis) needed for reaching high system integration levels (level ‘9’) for each of the shortlisted technologies.

Each innovation timeline highlights the critical and post-critical innovation needs, and the likely timelines required for shifting out of critical innovation investment periods and into whole system integration and deployment. It is assumed that whole system integration (post-critical innovation pathway) accelerates after full commercial readiness as cost-benefit analyses stack up for greater network adoption of technologies. The analysis confidence levels (right) indicate the reliability of these projections, with high confidence for technologies like superconducting cables and grid-forming technologies, and medium confidence for others like critical AI tools and quantum encryption. The timelines presented have been aligned with T/C/IRL findings shown for the deep dive technologies within this report and paired with presented deployment rates. Note that gas repurposing was not included due to the lack of specific technology needs.

Despite strong innovation needs in second-generation cables (focused on HTS as part of this analysis) as a viable superconducting cable option, lower commercialisation and readiness levels extend its critical innovation timeline where momentum needs to be kept for sustained deployment. HTS systems are currently more expensive than the equivalent cabling counterfactuals, but opportunities such as technology learning rates, economies of scale and contractor familiarity have the potential to reduce HTS costs to achieve parity. Fault management with HTS cabling still remains a substantial challenge to system integration[60] and strong R&D channels are needed by 2035 to significantly improve the commercial case and technological limitations within live systems. Similar timelines are seen with quantum-safe technologies in encryption / cryptography but there is less confidence due to limited network-specific trials (full integration timeline for this technology is the latest at ~2040). DLR, currently the only technology with a full technical readiness level, shows one of the shorter critical periods needed for innovation, similar to AI, dispatch algorithms, and grid-forming technologies which risk market failure or falling behind without higher public funding

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[60] High temperature superconducting cables and their performance against short circuit faults: current development, challenges, solutions, and future trends (Superconductor Science and Technology, 2022)

now. (E)HVDC and distributed feeder technologies also have shorter critical timelines but unlike the former suite of technologies, their innovation primarily lies in technological advancements despite some already sufficiently high TRLs.

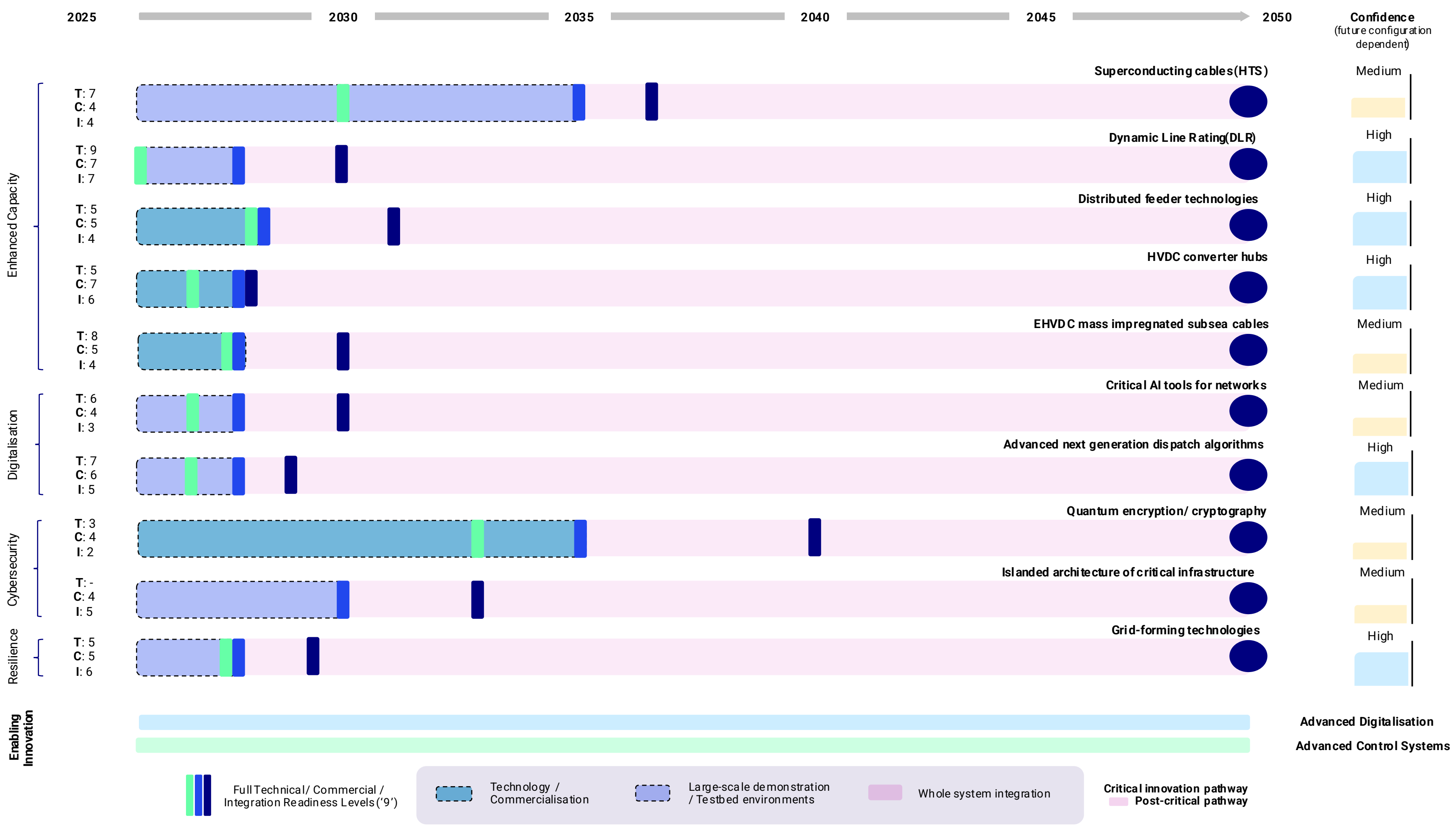

Figure 3: Infographic for conceptualising the innovation pathways and needed timelines, for the 10 shortlisted technologies, based on likely 2050 network configurations (analysis confidence shown to right).

Note: The diagram highlights the critical (based on achieving commercial readiness level of '9') and post-critical innovation needs where some technologies may demand shorter innovation interventions during their critical pathways. Readiness levels (T – green / C – blue / I – dark blue) and the relative timelines needed to achieve full 'readiness' (level '9') are shown and are based on various primary and secondary sources. Please note that these are best estimates of innovation needs and not exacting timelines. Gas repurposing not included due to limited techno-specific application.

Medium and Lower priority technologies

Medium and Lower priority technologies will also play key roles in meeting Net Zero targets, and many are critical enablers for wider system transformation. Appendix A.3 lists the *Medium*, *Lower*, and *Out of Scope* technologies assessed, many of which will be discussed as enabling technologies throughout this report. Figure 3 highlights two key enablers, advanced digitalisation and control systems, for wider system integration of shortlisted technologies. These two areas broadly cover many of the *Medium* priority technology areas, where public funding investment is important but are not critical for meeting Net Zero targets as there are substantiated levels of market momentum.

Table 3 shows the breakdown of the prioritisation categories where it is evident that digitalisation and control systems featured most heavily in the *Medium* and *Lower* priority technologies. While there are significant levels of investment in network digitalisation, operations, and control systems, and thus less justification for public funding, advancements in these technology areas are critical enablers for broader innovation.

Our analysis also highlighted that some technologies, despite their potential for radical system transformation, are too immature for public funding. Unlike quantum encryption, quantum computing remains predominantly in the R&D phase. While significant government support and investment exist, both in the UK and internationally, progress remains in its early stages. Since the establishment of the National Quantum Initiative in 2018, the US Department of Energy has funded a range of projects exploring how quantum computing can address challenges in energy technology development and energy system operation[61, 62]. However, the feasible development timelines do not align with the 2050 Net Zero targets, making it unsuitable for high-priority focus. Similarly, certain technology areas, such as digital twin applications, vary in maturity depending on the use case (specific asset digital models versus system- / region-wide models). While digital twins are experiencing greater investment across key projects[63], the innovation needs are varied, spanning across cost and resource efficiency, to scalability and real-time processing.

Conversely, technologies that enhance network capacity, such as modular-static synchronous series compensators (m-SSSC) and retrofit insulated cross arms (RICAs), offer substantial improvements in transmission efficiency. Despite the need for further innovation for system integration, the existing momentum justifies only medium-priority intervention for public funding. These arguments become clearer with Lower priority technologies. These areas are considered less critical for immediate funding due to earlier stages of development, less immediate impact on network performance, or are already being addressed through existing initiatives. Their lower priority (not ‘low’ priority) does not diminish their potential importance,

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[61] National Quantum Initiative (NQCO, Accessed November 2024)
[62] Quantum for Energy Systems and Technologies (NETL/DOE, Accessed November 2024)
[63] Iberdrola’s SP Energy Networks Acquires Derryherk to Boost UK Smart Grid and Support Net-Zero Goals (EuropaWire, Accessed October 2024)

and the same is true for out-of-scope technologies which are primarily assessed within other EINAs sector reports.

Beyond technological innovation

Techno-centric innovation is as much-needed as the various business model, legal, and planning innovations required to enable conducive network transformations. Investing in energy network technologies in the UK requires a balanced approach that combines techno-centric innovation with advancements in business models, legal frameworks, and planning processes.

While the EINAs identify specific technologies for public funding, these investments will not succeed if market and regulatory environments remain restrictive. As an example, technological advancements in grid-forming are crucial, but they must be supported by clear regulatory frameworks, flexible market structures, and stronger industry partnerships, to name a few, to create viable business models. Other areas such as superconducting cabling (see Second Generation Cables section) need large retraining programmes and workforce investments to realise required deployment rates.

Legal and regulatory frameworks need to evolve to allow new technologies to fully integrate in energy markets and wider system development while ensuring consumer protection. Additionally, planning processes must be streamlined to facilitate the approval and integration of new projects. However, significant barriers exist, including complex regulations, high initial costs, and integration challenges.

Barriers are particularly prominent within gas network innovation due to pressures to revisit business models and their role within a wider, more integrated energy system, largely underpinned by low-carbon electricity generation. Without addressing these barriers, even the most promising technologies may struggle to achieve widespread adoption, highlighting the need for a holistic strategy that fosters innovation across all aspects of the energy system.

Technology deep dives

The EINAs programme provides an economic analysis for prioritised technologies, assessing potential Gross Value Added (GVA) to the UK economy, domestic job creation, as well as an understanding of potential UK market share in the given technology. High-priority technologies in the network-specific focus were considered for this economic 'deep dive' if there was sufficient specificity in the technology (DLR presents a specific technology whereas AI tools do not), clear use cases for deployment (advanced control room dispatch algorithms are not appropriate, for instance), and sufficient data to model deployment and costs on a 5-year basis up to 2050 (grid-forming technologies lacked data to provide confidence in findings). Gas networks did not present any clear-cut technologies for these deep dives. The full methodology for deployment and economic modelling is described in the EINAs Methodology Report.

Superconducting cables (HTS), DLR, and distributed feeder technologies were considered for further economic assessment and are presented in the following subsections. Deployment profiles, under a high innovation scenario (including a baseline profile) for each of these technologies are presented in this section. These profiles are complemented by technical, commercial, and integration readiness levels (T/C/IRLs) and the necessary step changes needed to achieve full readiness (level '9'). It is assumed that deployment is accelerated once full commercial readiness is realised and the Enabling and Enabled sectors are also shown, with respective representation of timelines in which enablement occurs.

Economic analysis of prioritised technologies through this approach ensures focused investment and accelerates the development of critical innovations. The approach presented in this section and the business opportunities section is not a 'final assessment' of innovation needs and economic activity through strategic investments in these technologies, but a means to assessing the value of innovation in a replicable manner. It mitigates risks by allowing more thorough assessments, similar to the additionality that cost-benefit analyses (CBAs) bring to innovation projects. It also helps to align innovation priorities with national energy policies, ensuring market readiness and successful commercialisation. Overall, this strategy promotes a cohesive and effective path towards achieving sustainability and energy security.

Second-generation cables

Background, rationale, system drivers

Second-generation cables can significantly enhance the UK energy networks by enabling efficient, high-capacity power transmission with minimal energy losses[64]. They are particularly beneficial for urban areas where space is limited, yet demand is high across increasingly constrained networks. Second-generation cables represent the latest technological developments in transmission cabling, including high-emissivity cables and High Temperature Superconducting (HTS) cables. Guided by industry experts through stakeholder engagement as part of this EINA, this deep dive focuses on HTS cables. HTS cables[65] are particularly viable due to their ability to operate at higher (not 'high') temperatures using liquid nitrogen, which is cheaper and more environmentally friendly than low temperature (LTS) alternatives.

The primary drivers for innovation in HTS cabling include the need for enhanced grid capacity, and improved energy efficiency along transmission networks. HTS cables can address these needs by providing higher capacity transmission with lower energy losses compared to conventional cables. The technology's ability to accelerate renewable energy integration further underscores its viability for innovation and public investment, and with a significantly higher current (not necessarily voltage) capacity and reduced installation times, HTS is a practical choice for modernising grid infrastructure.

Existing deployment scenarios in the literature, such as those explored in the SCADENT project[66], suggest that HTS cables could be integrated into urban power networks to handle the growing electricity demand, especially in densely populated areas. However, use cases remain specific to transmission connections to distribution systems[67] and there has been significant network inertia (uptake / development) due to unattractive CBAs when presently compared to counterfactual copper-based solutions. Due to the large risk environment, one where networks recognise the need but display hesitance to change, public funding for HTS cabling can stimulate more favourable markets.

Innovation needs and required step changes

Reducing costs, improving operational requirements and lifespans, demonstrating clear use cases for deployment are all key innovation needs. To fully realise the potential of HTS cables, several innovation needs must be addressed which include advancements in material science to improve the performance and reduce the cost of superconducting materials, as well as the development of efficient cooling systems (warm vs. cold dielectric designs) to maintain

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[64] A tenth of all electricity is lost in the grid. Superconducting cables can help (The Conversation, Accessed Oct 2024)

[65] High Temperature Superconductor (HTS) Cables (ENTSO-E, Accessed Nov 2024)

[66] Super Conductor Applications for Dense Energy Transmission – SCADENT (ENA Innovation Portal)

[67] Design and economic analysis of 275 kV HTS cable for UK transmission network (University of Strathclyde, 2024)

the required low temperatures. When the latter costs fall, HTS becomes a much more attractive business proposition for networks[66]. A significant step towards reducing HTS costs is the US Department of Energy's (DOE) Project Arch, a $80 million initiative to establish a large-scale HTS wire manufacturing facility in the southeastern US. This facility is expected to significantly reduce the cost of HTS wire production and accelerate commercialisation[68].

Primary areas of innovation emphasis encompass the discovery of novel superconducting materials, enhancements in fabrication techniques, advancements in cooling technologies, and strategies for integrating with current power grids[69]. Key advancements of the cooling systems (which make up one third of CAPEX) include the development of closed-cycle refrigeration systems and cryocoolers to enhance cooling efficiency which minimising energy consumption. Discovering (i.e., continued RD&D) new superconducting materials with higher critical temperatures (Tc) and better mechanical properties is crucial for improving performance and reducing cooling demands. Enhancements in fabrication techniques are necessary to optimise system functionality. Additionally, research into hydrides under high pressure and near-room-temperature conditions presents promising alternatives for improved cooling performance, although timelines for the commercialisation of material discoveries tends to be slow. Finally, innovations in thermal management and insulation materials will play a vital role in maintaining stable cryogenic conditions and extending the lifespan of HTS cables69 above[69].

Demonstrations of hydrogen-electricity hybrid energy transmission and advanced refrigeration cycles highlight promising areas for innovation in the cooling systems of HTS cables. Although currently laboratory-based / early demonstration phases, the use of liquid hydrogen as both an energy carrier and a coolant presents a dual-purpose solution that could enhance the efficiency and sustainability of HTS power transmission. By utilising surplus renewable energy to generate liquid green hydrogen, this approach integrates energy storage with HTS technology, while liquid hydrogen can serve as a protective buffer, improving thermal stability[70]. Additionally, the exploration of cooling systems incorporating both Turbo-Brayton refrigerator cycles and Stirling refrigerators suggests opportunities for improving efficiency and reliability[71]. These technologies could provide more effective and scalable cryogenic solutions, reducing energy consumption and operational costs. Together, these demonstrations indicate that future innovation should focus on optimising hybrid cooling strategies, integrating renewable energy sources, and refining refrigeration cycles to enhance the practicality and performance of HTS cables.

Figure 4 shows the deployment profile used in the economic analysis for HTS cables, where a generalised profile is given under a high innovation scenario, with a baseline for comparison. The T/C/IRL of HTS cables currently reflect a development stage where pilot

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[68] MetOx Secures $80M in DOE Funding to Build Advanced HTS Wire Manufacturing Facility in the U.S. (Sunya, Accessed November 2024)

[69] Superconducting Materials for Power Transmission: Development and Challenges (Singh, Tyagi, and Dwivedi, 2024)

[70] Hydrogen-electricity hybrid energy pipelines for railway transportation: Design and economic evaluation (Fu *et al*., 2024)

[71] Cooling system for China’s 35 kV/2.2kA/1.2 km high-temperature superconducting cable achieves two-year successful operation (Han, Zong and Xie, 2024)

projects are feasible, but widespread deployment in the UK requires considerable R&I and commercialisation. CRL and IRL levels in particular need to be enhanced through targeted research and development efforts. It is also important to note that HTS TRL is higher for AC networks versus DC connections. Under high innovation (assumes high public funding support to meet innovation needs), estimated timelines suggest that accelerated rates of deployment of HTS cables could be achieved by 2035, with wider adoption by electricity networks by 2040.

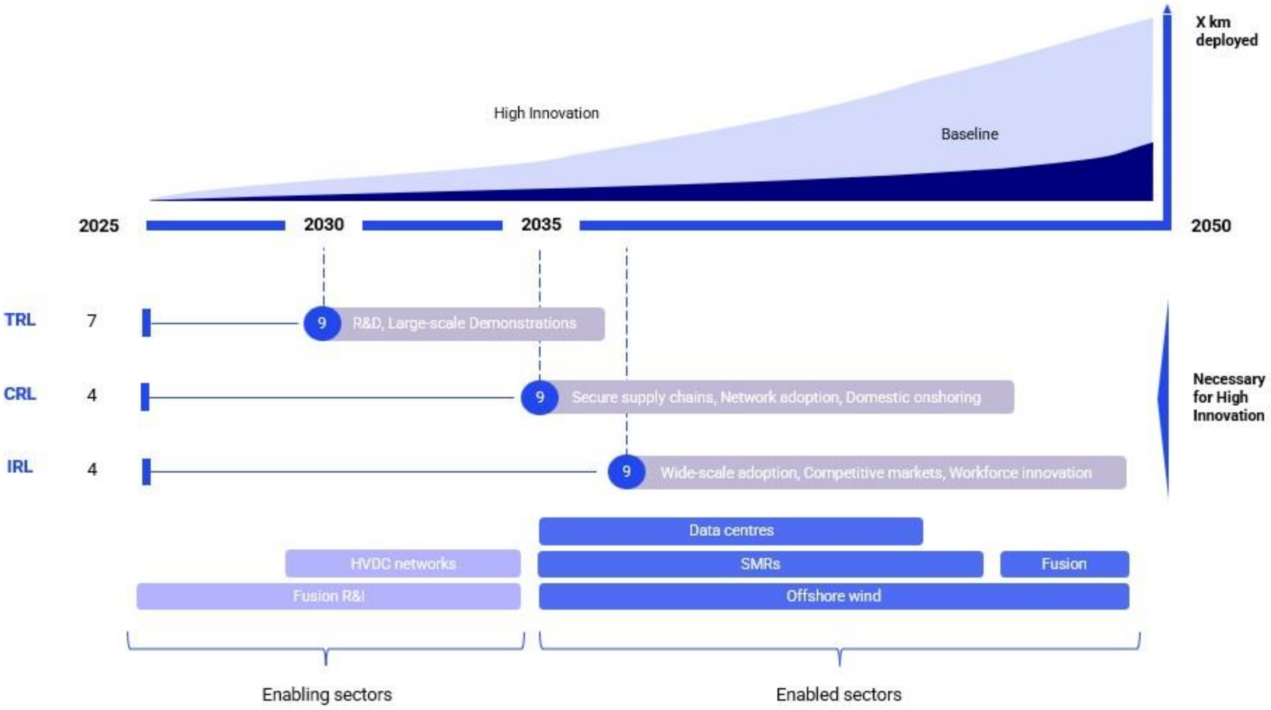

Figure 4: Deployment profile for high temperature superconductor (HTS) cables in the UK under a high innovation scenario, with a baseline profile also shown.

Note: This diagram is complemented by technical, commercial, and integration readiness levels (T/C/IRLs) and the necessary step changes needed to achieve full readiness (level '9'). It is assumed that deployment is accelerated once full commercial readiness is realised and the Enabling and Enabled sectors are shown below, with respective representation of timelines in which enablement occurs.

HTS is being driven by key (yet nascent) industries such as fusion and SMRs, but deployment pathways are unclear. Despite the significant role that HTS and other superconductors can play in future network systems, the current network inertia towards more wide-scale adoption, and the lack of demonstration on live systems in the UK, present major barriers to overcome. While a great derisking opportunity for public funding, the near-term future of HTS is less certain in the absence of key innovation projects and trials. This is particularly true with HTS uptake across certain use cases and industries such as HVDC connections and within data centres (private wires etc.), where data and pilot projects have not gone far beyond limited testbeds.

Achieving these milestones will require coordinated efforts across the supply chain, including manufacturing, installation, and maintenance. While some UK-based companies are making notable strides in HTS R&I and integration[72], ensuring effective innovation in deployment and technological advances will require a whole system approach. Barriers extend beyond the technical limitations and networks will need to alter existing business and operation models in order to accommodate HTS and the skilled workforce required to make deployment a reality.

Competitive advantage and supply chain risks

The UK has a medium competitive advantage in HTS cable technology due to its strong research base and expertise in advanced materials. Advances in nuclear technologies, data centre growth and R&I, and demand from offshore technologies and their connections are key areas where HTS is gaining more visibility though innovation and deployment are very low, with little to no deployment currently (2025) in the UK. Even with these barriers, the foundational enabling sectors are present and provide HTS innovation opportunities. Key UK market strengths include a robust innovation ecosystem and established collaborations between academia and industry. However, global competitors such as France, China, Japan, and Germany are also investing heavily in HTS technology, with some leading companies including Nexans, Sumitomo Electric, and American Superconductor.

To catch up and build the foundational platform to compete globally, the UK must strategically invest in research and development, support the scaling up of manufacturing capabilities, and foster international partnerships. Public funding can play a crucial role in these efforts, ensuring that the UK remains at the forefront of HTS cable innovation and deployment.

Dynamic Line Rating (DLR)

Background, rationale, system drivers

Although networks are very familiar with DLR, the technology is a significant innovation in the field of electrical transmission, designed to optimise the capacity of existing power lines by dynamically adjusting their ratings based on real-time conditions[73]. Unlike traditional static line ratings, which use conservative estimates, DLR uses sensors and advanced analytics to assess the actual capacity of power lines, considering factors such as temperature, wind speed, and line sag. This technology is particularly relevant for the UK energy network (transmission) as it can enhance the efficiency, monitoring, and reliability of the grid, accelerating the integration of renewable energy sources.

The primary drivers for innovation in DLR technology include the increasing grid electrification, the need for greater grid flexibility, and the rapid integration of renewable energy sources. As the UK aims to decarbonise its energy system, the ability to dynamically manage grid capacity becomes crucial. DLR can help accommodate the variable nature of

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[72] SuperNode Expands Operations with New Cable Technology Centre in Blyth, Northumberland (Supernode Energy, Accessed Oct 2024)

[73] Dynamic Line Rating Innovation Landscape Brief (IRENA, 2020)

renewable energy by providing real-time line capacity data, thus mitigating congestion, and reducing curtailment. This line sensing is very important in constrained periods of higher system strain and tightness. Pervious trials have demonstrated an intraday rated capacity being raised up to 130% through DLR implementation (under specific weather conditions)[74].

The current state-of-play includes successful trials which have demonstrated the potential to unlock additional capacity and reduce operational costs. National Grid have invested directly into LineVision[75], a US-based company and the world's only provider of non-contact overhead power line monitoring systems, for the deployment of DLR across their network[76]. Initial findings from US-based network trials demonstrate that DLR is able to unlock ~0.6GW of additional capacity and save £1.4 million in network operating costs per year[75]. DLR's ability to maximise the use of existing infrastructure, through non-contact sensing (with no installation downtime), minimises the need for additional network build-out and allows for a more rapid penetration of connections to the transmission system. Building on this, National Grid's RIIO-3 submission details the organisations Enhanced Rating Strategy, including innovation successes to date (£1.5m spent on enhanced services resulting in a reduction of constraint costs and providing consumer savings of more than £150m)[77] and ambitions to increase the use of weather-based enhancements supplemented with targeted sensor-based systems[78].

Innovation needs and required step changes

To fully leverage the benefits of DLR technology, several innovation needs must be addressed. These include the development of more advanced sensors and data analytics platforms to improve the accuracy and reliability of real-time measurements. As seen in Figure 5, the TRL of DLR is currently, on average, at full readiness (due to successful and live demonstrations) where innovation needs primarily exist around ampacity calculations during live monitoring to accurately account for real-time data and the impacts of environmental and line conditions.

DLR is at a stage where demonstration projects and live monitoring are feasible, but widespread deployment requires further advancements in sensor technology and data integration. CRL and IRL also need to be enhanced through targeted research and development efforts. Digitalisation is a large part of DLR integration, particularly for no-contact solutions and this spine of sensing and communications requires effective data streams. AI and big data processing algorithms will enable greater implementation of DLR across UK networks, while renewables and demand-side (consumer-led) services are poised to see further uptake due to DLR high innovation.

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[74] Dynamic Line Rating (DLR) (ENTSO-E, Accessed on Oct 2024)
[75] National Grid trials new technology which allows more renewable power to flow through existing power lines (National Grid, Accessed Oct 2024)
[76] LineVision was a key stakeholder in our analysis and results reflect data and learnings pulled from engagements and modelling.
[77] RIIO T3 – Innovation Annex (National Grid, Accessed April 2025)

Scottish Power Energy Networks (SPEN) and National Grid detail DLR innovation projects within their RIIO-3 submissions. As discussed above, National Grid's Enhanced Rating Strategy combines funding from partners, innovation stimulus funding and NIA funding focusing on deployment of dynamic ratings across their network[78]. SPEN's RIIO-3 innovation strategy outlines that the Phoenix NIC project which combines real-time thermal rating systems providing boundary capacity and system strength with installation of hybrid synchronous compensators is to be completed in 2026[79].

Estimated timelines suggest that significant deployment of DLR technology could be achieved by 2030, with wide-scale adoption by network companies by 2035. Achieving these milestones will require rapid and further commercialisation of DLR systems, as well as increased confidence in real-time sensing of networks in more difficult terrains and weather conditions (wind and temperature profiles can have considerable impacts on DLR). Regulatory environments may also need to adapt whereby adequate funding can be accessed for these monitoring upgrades.

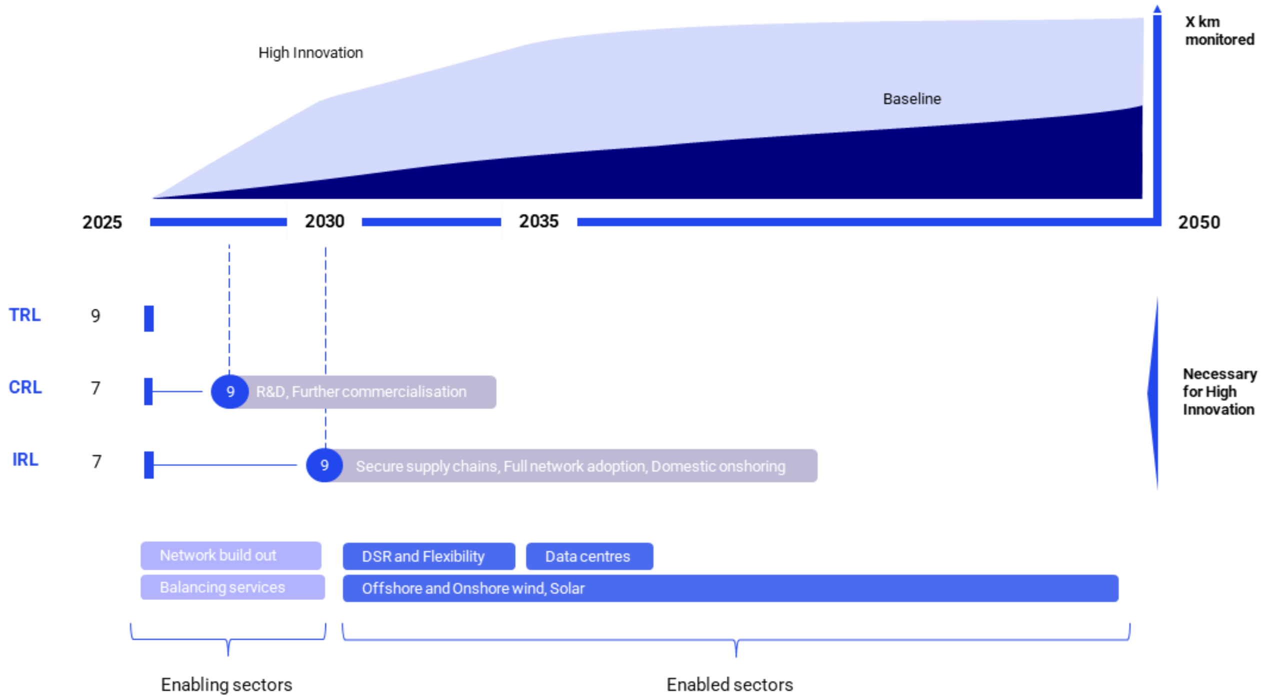

Figure 5: Deployment profile for dynamic line rating (DLR) sensing in the UK under a high innovation scenario, with a baseline profile also shown.

Note: This diagram is complemented by technical, commercial, and integration readiness levels (T/C/IRLs) and the necessary step changes needed to achieve full readiness (level '9'). It is assumed that deployment is accelerated once full commercial readiness is realised and the Enabling and Enabled sectors are shown below, with respective representation of timelines in which enablement occurs.

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[78] Enhanced Ratings Strategy (National Grid, Accessed March 2025)

[79] Innovation Annex - RIIO-T3 Business Plan - SP Energy Networks (Scottish Power Energy Networks, Accessed April 2025)

Competitive advantage and supply chain risks

The UK has a competitive advantage in DLR technology due to its strong research base and expertise in grid management. National Grid's strategic investment in LineVision sends strong signals for future DLR implementation and public funding can support this technology in its prime 'lift-off' phase. Given domestic expertise and research activity, the UK is well-positioned to become a leader in the global market for DLR technology, with potential for significant export opportunities if manufacturing is successfully onshored. However, there are barriers hindering collaboration and wider deployment. UK-based companies working in this space are mostly SMEs and currently lack the capacity to engage effectively with network operators.

Global competitors such as the US, Germany, Belgium, China, and many others are very closely in tow, if not ahead, and are also investing heavily. Leading companies in this field include LineVision and Ampacimon. Public funding can play a crucial role in building on existing investments and IP, primarily where manufacturing is concerned as network monitoring is likely to increase sharply in the coming years. These efforts will ensure that the UK pushes ahead with DLR technology innovation and deployment.

Distributed feeder technologies (DFTs)

Background, rationale, system drivers

Distributed feeder technologies play an essential role in modern energy networks, particularly in electricity distribution systems. These technologies encompass devices like Distributed Static Compensators (D-STATCOMs), Distributed Soft Open Points (D-SOPs), and Distributed Smart Transformers (D-STs), which manage voltage and thermal congestion, and improve power quality by addressing issues such as voltage imbalance. Their primary function is to enhance the capacity and reliability of the distribution network, thus supporting the integration of LCTs like EVs and heat pumps. The key system drivers behind the increased use of distributed feeder technologies in UK energy networks include the need to accommodate the growing penetration of LCTs, the imperative to maintain power quality and reliability, and the economic benefits of deferring costly network reinforcements.

The current state of play for these technologies includes various UK-based and international trials demonstrating their effectiveness. For instance, the D-Suite project has conducted trials across six low voltage (LV) distribution networks in the SP Energy Networks service territory, showing potential societal benefits through congestion mitigation and reinforcement deferral[80]. These trials have highlighted the effectiveness of D-Suite devices in managing voltage and thermal congestion, as well as improving power quality and the project has also demonstrated the potential for significant cost savings through the deferral of traditional network reinforcements (where extensive delays due to planning and land

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[80] D-Suite (ENA Innovation Portal, Accessed Nov 2024)

acquisition delay necessary substation upgrades). Internationally, the use of distributed feeder technologies is also gaining traction. In Europe, feeder automation systems are being implemented to increase the efficiency and quality of electric service, with research and development efforts focused on communication technology to make distribution automation more cost-effective and efficient[81].

The fundamental system drivers for distributed feeder technologies in the UK also include the economic benefits of deferring costly network reinforcements which are significant. As distributed feeder technologies can provide a cost-effective alternative to traditional reinforcement methods, their integration and further deployment on current network infrastructure can help to optimise the use of existing assets, reduce operational costs, and improve overall network performance.

Innovation needs and required step changes

Several key innovation needs must be addressed and include the optimisation of device placement within the network, and the enhancement of device utilisation rates (these devices 'step in' to meet peak demand). Additionally, there is a need for systematic approaches to integrating these technologies into existing network infrastructure. The high cost of these power electronic devices (PEDs) is a significant barrier to their widespread adoption, and reducing these costs is essential for increasing their deployment. This can be achieved through strategic onshoring of manufacturing processes, economies of scale, and the development of new materials and technologies. Future cost reductions in PEDs could make distributed feeder technology devices more economically viable, while optimised placement strategies could further minimise investment costs and maximise the benefits of these technologies. Figure 6 shows that a rapid T and CRL advancement is needed in order to deploy at pace with peak deployment being achieved by 2035. The placement of distributed feeder technologies is critical to their effectiveness. This can be achieved through the use of advanced modelling and simulation tools, as well as real-time data and analytics (as seen through the D-Suite project). The enhancement of device utilisation rates is another key innovation need and rates can be improved through the integration of smart sensors and IoT (Internet of Things) devices, which provide real-time data and analytics for better decision-making. The application of AI through automation and control technologies can quickly isolate faults and restore power, minimising the impact of outages. Additionally, there is a need for regulatory support and incentives to encourage the adoption of these technologies, as well as investment in R&D to drive innovation and reduce costs[82].

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[81] Distribution Feeder Automation System Market Size, Share, and Industry Analysis by Product (Fortune Business Insights, Accessed Nov 2024)

[82] Seasonal Cost-Benefit Analysis of Automated Distribution Feeder Upgrades with Advanced Mitigation Technologies (NREL, 2024)

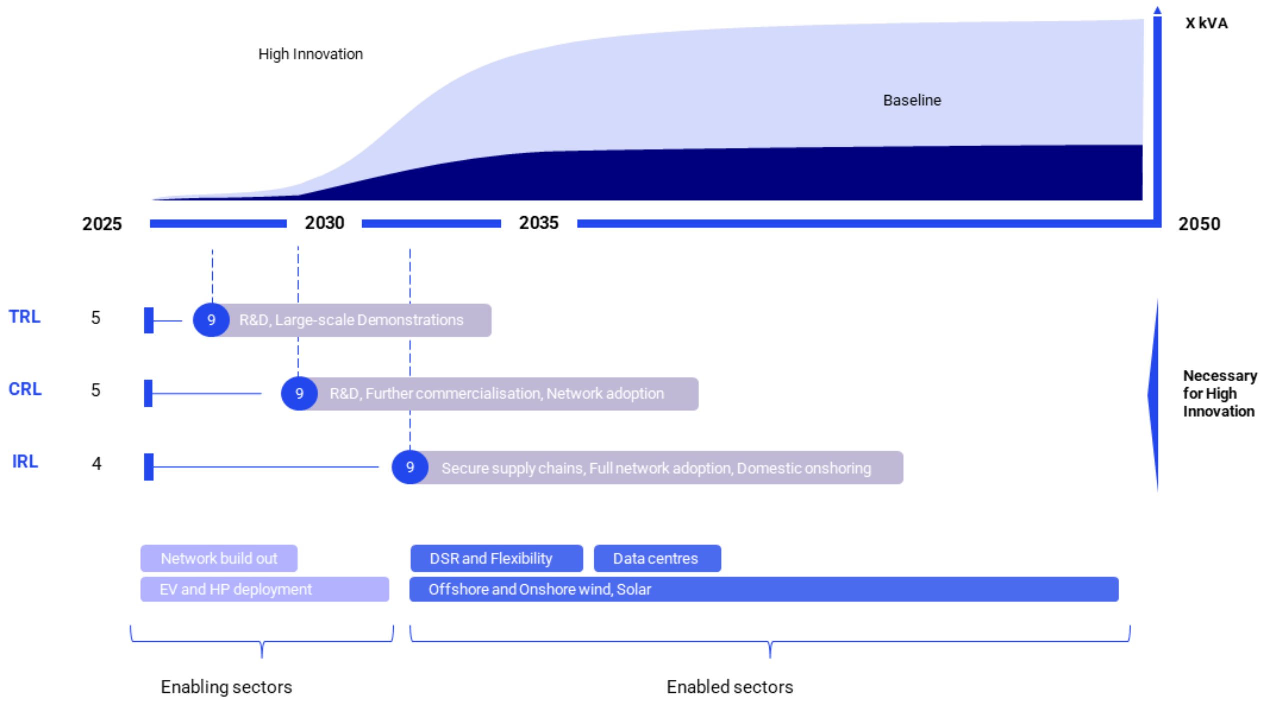

Figure 6: Deployment profile for distributed feeder technologies in the UK under a high innovation scenario, with a baseline profile also shown.

Note: This diagram is complemented by technical, commercial, and integration readiness levels (T/C/IRLs) and the necessary step changes needed to achieve full readiness (level ‘9’). It is assumed that deployment is accelerated once full commercial readiness is realised and the Enabling and Enabled sectors are shown below, with respective representation of timelines in which enablement occurs.

Competitive advantage and supply chain risks

The UK has a competitive edge in distributed feeder technologies, thanks its expertise in power electronics and a robust research ecosystem. Its strong regulatory frameworks, net-zero commitments, and energy systems innovation further enhance this advantage. The UK is home to numerous leading universities and research institutions that focus on advanced power electronics, solid-state devices, and energy conversion systems. Additionally, the UK government has established various funding programs and innovation hubs, such as Innovate UK and the Catapult centres, which support the development and commercialisation of advanced power electronics technologies. Currently, the UK has no large manufacturer of the power semiconductors required. The ‘Driving the electric revolution’ challenge programme, ran by Innovate UK, was a recent initiative aimed at supporting the UK better capture the economic opportunities of power electronics, machines, and drives (PEMD) products. The programme has provided investment in component technology, to develop the next generation of products using PEMD, filling gaps in electrification supply chains, skills and funding centres[83].

Moreover, the UK's industrial landscape includes several key players in the power electronics sector, such as Rolls-Royce, Siemens UK, and Schneider Electric UK, which contribute to the country's leadership in deepening wider system integration of critical technologies. These companies are involved in the design, manufacturing, and deployment of PEDs that are crucial for the efficiency and reliability of energy networks. The combination of academic excellence, industrial expertise, and supportive government policies positions the UK as a leader in power electronics, but key innovation needs are still present in the deployment of distributed feeder technologies as outlined in the previous subsections.

The UK's position is bolstered by leadership in clean tech patents and attracting investment in innovative energy solutions. However, supply chain risks include the high costs of PEDs, delays in new technology integration, and the need for skilled personnel. Reducing PED costs through better manufacturing, economies of scale, and new materials is essential, and further regulatory support, R&D investment, and training programs are crucial to address these challenges and ensure successful deployment.

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[83] Driving the electric revolution (UKRI, Accessed January 2025)

Business opportunities in electricity networks

Key Chapter takeaways

- A cumulative contribution from the three deep dive technology areas assessed of between £0.20bn and £1.15bn in GVA between 2025 and 2050[1]. A corresponding increase in supported (direct and indirect) job creation to between 150 and 800 by 2050, in the low and high innovation scenarios respectively. The level of employment supported is largely consistent between 2035 and 2050.
- The deployment forecasts drive projections that distributed feeder technology solutions would account for up to 76% of the annual economic contribution of the three network technologies by 2050 with medium innovation.
- In the medium and high innovation levels, HTS makes a 45%-74% larger contribution to cumulative GVA over the period than DLR, yet, as detailed in 5.1, there is higher uncertainty and risk with HTS funding.
- In the low innovation scenario, DLR contributes 39% more than HTS. This is due to an expectation that the deployment of DLR will be less sensitive (elastic) to innovation than the deployment of the other two technologies.
- The deployment of networks technologies is largely front loaded, which means the kinds of jobs shift from being principally CAPEX-focused early on in the period (2025-2035) to then more OPEX-focused by 2050.
- Highly skilled science, research, engineering, and technology professional roles could make up over a third of all direct jobs by 2050, a proportion that is consistent across innovation levels.

Overview

The purpose of this section is to explore the potential scale of economic opportunities for the UK associated with the national and global development of three of the key technologies discussed in this report: DLR, HTS, and DFTs. Innovation has the potential to be a key driver in supporting the growth of this sector in the UK and realising these economic opportunities, and therefore an important element to capture as part of this innovation assessment.

The section draws on the key findings from the development of a series of 'business opportunities calculators'. These calculators are built on projections of domestic deployment of the three technologies derived from engagement with academic and industry leaders.[84] They combine this understanding of potential deployment with assumptions around the cost structure and employment intensity of the different activities required for the manufacturing, deployment, operation, and decommissioning of each technology to generate an understanding of the potential economic opportunities in terms of:

- Gross Value Added (GVA): a measure of the value generated by the production of goods and services. GVA can be thought of as broadly equivalent to the contribution of that sector / activity to Gross Domestic Product.
- Employment: measured in terms of jobs and includes both direct employment (the jobs associated with the construction, operation, and decommissioning of the assets), and indirect employment – the jobs associated with the production of the goods and services needed by the workers with direct jobs i.e., jobs associated with the supply chain needed to construct, operate, and decommission assets.

All results are illustrative of potential economic impacts of technological innovation. They are generated using a particular set of technologies, hypothetical deployment scenarios, modelling outputs and other assumptions to help inform UK Government decision making. The modelling outputs on which the results are based include modelled expectations for deployment in both 2020 and 2025. While efforts have been taken to calibrate these modelled outcomes with existing deployment data, some inconsistencies will remain. Looking forward, results do not reflect UK government targets/ambitions regarding neither deployment of these technologies nor the economic opportunities that might be realised.

It is also important to stress that the results are specific to the three technologies of focus for the report (DLR, HTS, and DFTs), rather than the GVA and employment for the wider energy network sector which is composed of a significantly larger array of technologies. As such, care should be taken when comparing the figures presented below with estimations which cover the entire sector and use different scenarios and models.

All monetary values in this section refer to 2022 GBP unless otherwise specified. The methodologies for the calculators, along with key caveats and assumptions, are available in the EINAs Technical Methodology report.

Networks business opportunity analysis

Gross Value Added (GVA)

As Figure 7 shows, the business opportunities calculators suggest that the GVA contribution of these technologies will increase over the period but the scale of this increase varies significantly depending on the level of innovation achieved – quicker deployment of the technology in the higher innovation scenarios leads to a higher level of GVA. The difference in GVA contribution between the innovation levels is most marked between 2030 and 2035. After

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[84] Due to a lack of data on future global deployment, it was not possible to reliably forecast the size of the potential export opportunity for these technologies.

2035, GVA broadly stabilises in all innovation levels on the back of deployments rates stabilising to roughly the same extent in all three scenarios. Cumulatively, the high scenario suggests that up to £1.15 billion in GVA could be generated across the period between 2025 and 2050 (£46 million per year on average), almost six times more than the £0.20 billion over the same period (£8 million per year on average) in a low innovation scenario.

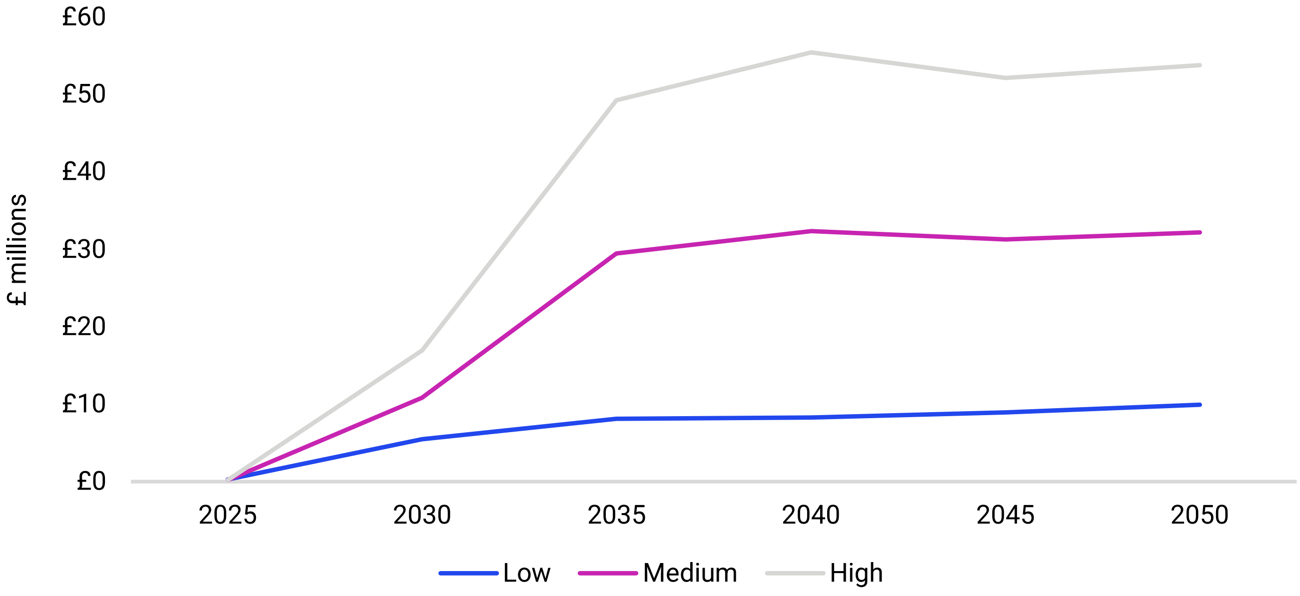

Figure 7: Total GVA by innovation level across considered technologies.

Across the three innovation levels and the modelling time horizon, distributed feeder technologies are expected to contribute the vast majority of the GVA generated by these three networks technologies. As shown in Figure 8. In 2035, DFTs account for between 83% and 87% of GVA, dropping to between 65% and 79% in 2050. The only case where DFTs contribution is expected to drop below 75% is in 2050 in the low innovation scenario. This is driven by DLR having a less dramatic variation in deployment between the high and low innovation levels, compared to the other two technologies, such that, assuming a low level of innovation, the technology makes a relatively larger contribution to GVA. The dominance of DFTs GVA contribution means that most of the variation between the innovation levels at the aggregate level is driven by the variation in DFT deployment between the different innovation levels. There is potential for a significant shift in performance and cost with the ongoing development of high-bandwidth semiconductors like Silicon Carbide (SiC) and Gallium Nitride (GaN). This is not accounted for in the scenarios assessed, therefore, Figure 8 presents a slower and steadier picture for DFT innovation.

In the medium and high innovation levels, HTS makes a 45%-74% larger contribution to cumulative GVA over the period than DLR. There are significant risks involved with HTS innovation given uncertainty around requirement for advances in the physical properties of the materials involved and cooling. However, given the potential added capacity delivered through this cable technology, their impact can quickly be scaled up from niche use cases (such as transmission to distribution interfacing in urban centres) to a more prominent role in the network across various asset.

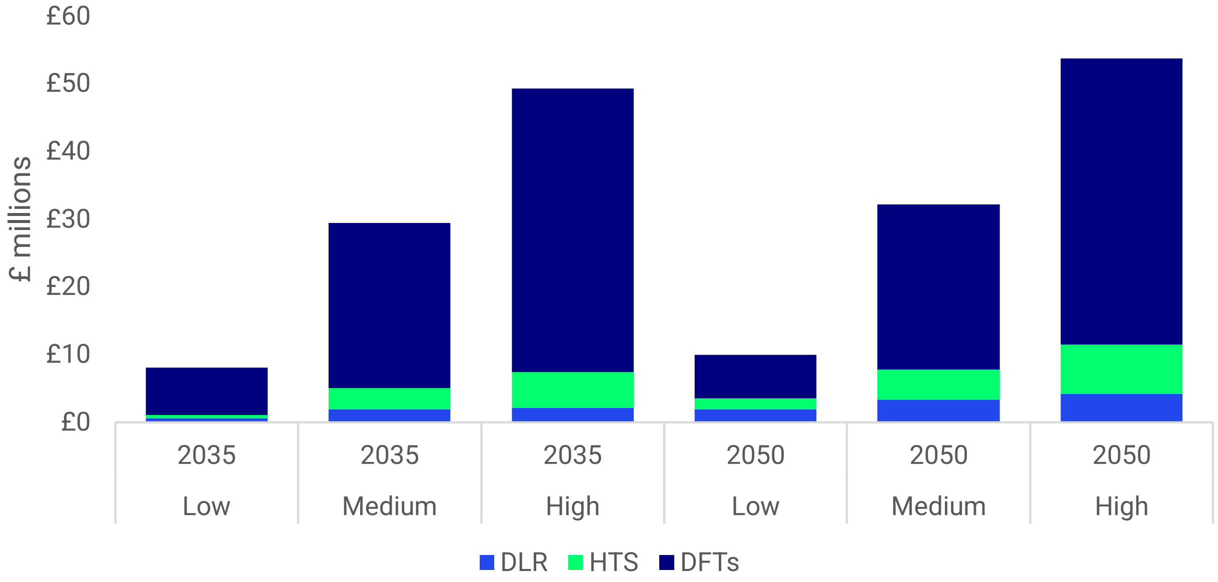

Figure 8: GVA by innovation level, by considered technology.

Direct and indirect jobs

Figure 9 shows that supported employment follows the same general trend as for GVA and the trends of deployment. Between 2035 and 2050, these technologies are expected to support between around 120 – 150 additional jobs in the UK with low innovation and as many as between 770 and 870 additional jobs with high innovation[85].

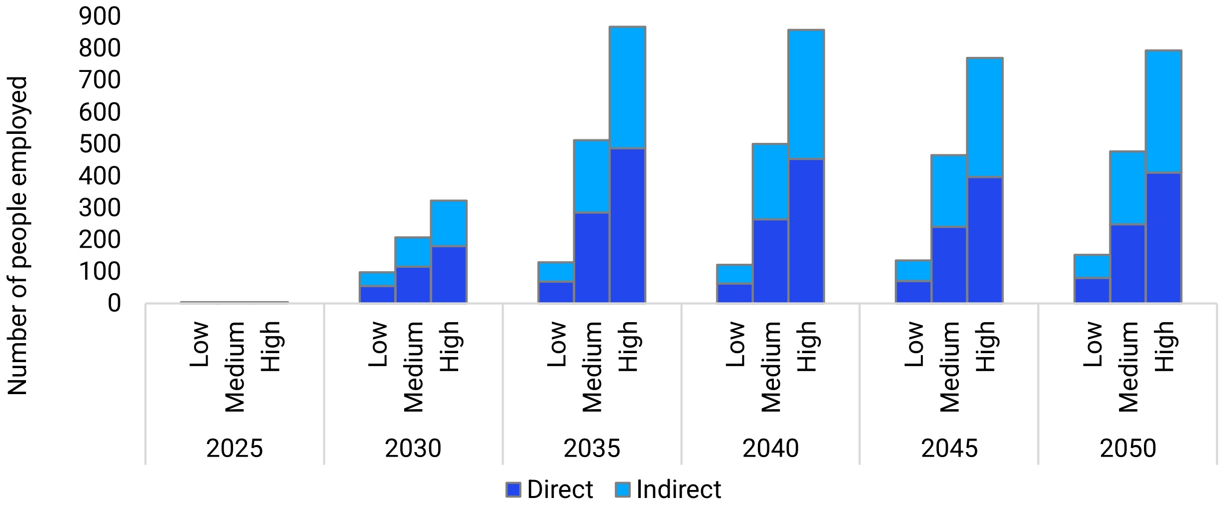

Figure 9: Total jobs supported in year (direct vs indirect) supported by innovation level for considered technologies.

Across all innovation levels and the modelling time horizon, direct jobs account for between 51% and 56% of the total number of jobs supported implying that every direct job is expected

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[85] Note that these values are a conservative estimate of jobs due to the analysis having data limitations on deployment, only considered the three technologies assessed, limited visibility in other sectoral developments happening in parallel that can lead to a collective uplift, and a limitation around fully accounting for R&D jobs before deployment (2025 and earlier) for each technology.

to lead to one additional indirect job. This relatively low 'multiplier' is because of the relative capital intensity of electrical equipment and electronic manufacturing, the key activity in the supply chain. Between the years 2035, 2040, and 2045, there is a decrease in the number of people employed. This trend is connected to rapid deployment from 2030 to 2035, following which a number of jobs transitioned from initial development and CAPEX-based roles to those focused on operation and maintenance.

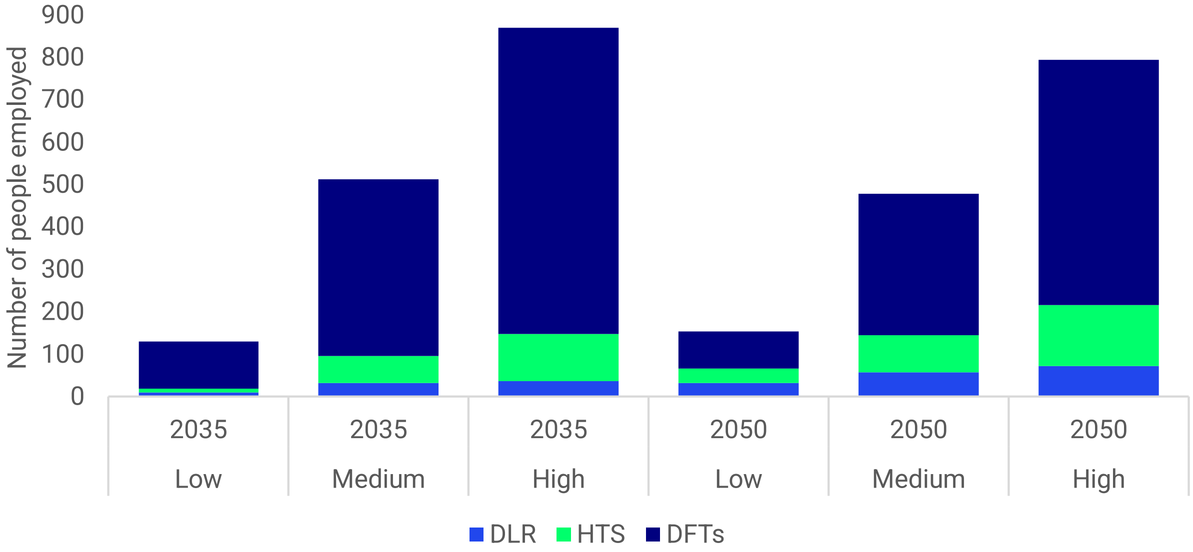

Figure 10: Total jobs supported (direct + indirect) by innovation level, by considered technology.

Building on the discussion above, Figure 11 illustrates the projected distribution of employment across cost categories. As expected, given the deployment profiles, jobs in 2035 are dominated by CAPEX activities with jobs in 2050 being dominated by OPEX activities. OPEX on the other hand becomes much more important by mid-century with all the assets deployed across the time period needing to be operated and maintained.

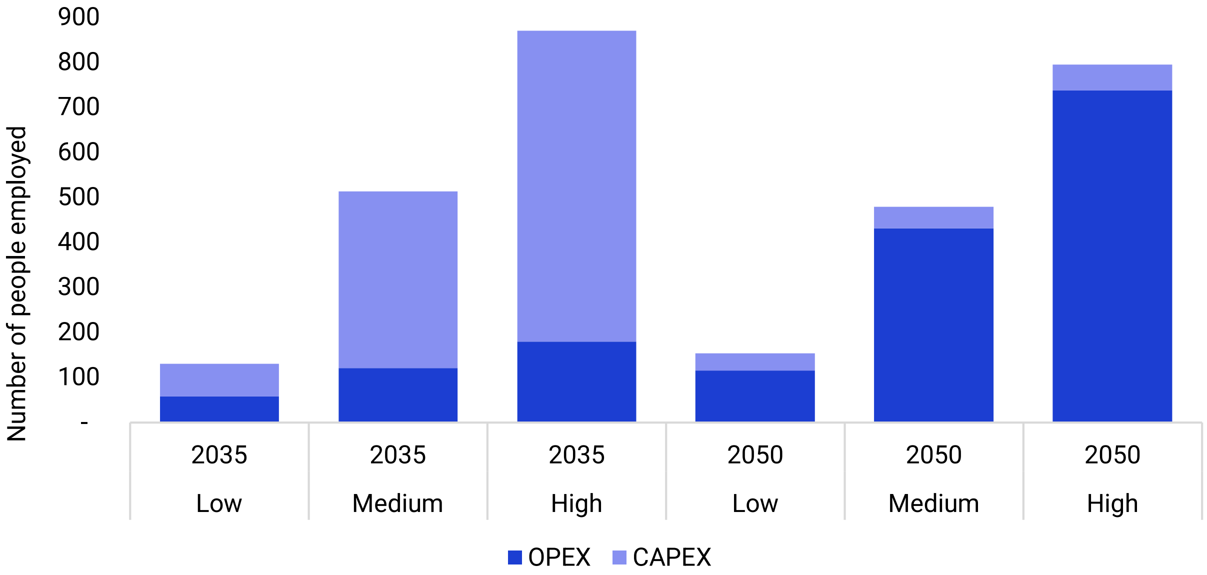

Figure 11: Total jobs supported (direct + indirect) by innovation level, by cost category.

Finally, Figure 12 below, showing the possible distribution of supported direct jobs in 2050, illustrates that the development of these technologies can support jobs across a wide range of different occupations. The distribution of jobs between occupation types is highly consistent between innovation levels. The largest share of jobs, in all innovation levels, involves highly skilled science, research, engineering, and technology professional roles which make up between 36% and 37% of direct jobs. These jobs will principally be supported by a large number of jobs in administrative and secretarial occupations (21-23% of direct jobs) and associate professional occupations (21-24% of direct jobs).

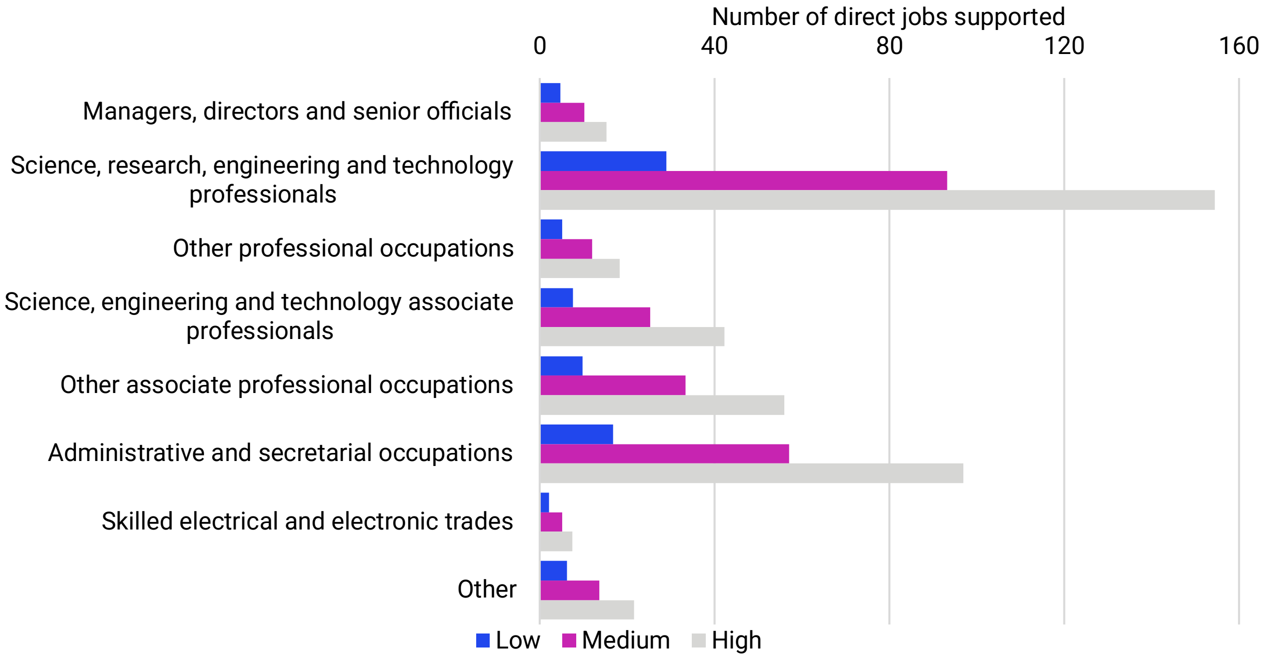

Figure 12: Direct jobs supported by innovation level, by occupation type in 2050.

Notes: For the purposes of this analysis, the 412 4-digit SOC codes have been aggregated to 15 SOC groupings. See the EINAs Technical Methodology note for more details on this aggregation. In Figure 12 the heading ‘other’ covers the following 8 SOC groupings: elementary occupations; skilled metal trades; skilled construction and building trades; other skilled trade occupations; process, plant and machine operatives; transport and mobile machine drivers and operatives; sales and customer service occupations and caring, leisure and other service occupations.

Criticality of networks to enabling the wider energy transition

Key Chapter takeaways

- Innovation across considered technologies can significantly reduce the size and cost of required transmission infrastructure. While scenarios vary, higher levels of innovation generally lead to lower costs and less infrastructure needed, especially in typical weather years.
- High innovation causes transmission cost reductions (overall in assessment year) of 6% to 10% across EINA technologies. Total transmission cost in the scenarios (UK TIMES) and innovation cases modelled ranges between £1.6 and £2.1 billion in 2050, with the counterfactual baseline showing one of the highest predicted costs.
- Given the increasing necessity to transport renewable energy from Scotland to demand centres located further south, zones UK2, UK3, and UK4 (Scotland to North/Central East England) are projected to experience the highest transmission network capacity requirements in both 2035 and 2050.

Overview

System modelling to assess the potential impact of innovation in key Net Zero technologies was conducted for the EINAs primarily using UK TIMES, an energy system model of the UK that was developed by UCL and the UK Department of Business, Energy and Industrial Strategy (now the Department for Energy Security and Net Zero or DESNZ). For each of the selected technologies, three levels of innovation were developed representing a low, medium, and high innovation case for the technology. The low innovation represents a business-as-usual case where innovation follows recent trends or is generally limited, whilst the high innovation case represents significant innovation in the technology to decrease costs and improve efficiencies.

The low, medium and high innovation cases were each run against three different hypothetical scenarios which were developed by DESNZ to represent potential routes to net zero for the UK, namely Minimally Constrained, High Hydrogen and High Diversification. They do not represent government policy or forecasts but were selected due to their differing constraints which provide a diverse set of outputs and insights. A summary of each is presented below, a more in-depth description can be found in the methodological report.

- **Minimally Constrained**: Designed to show the largest potential impacts from innovation investments by minimising the number of constraints on the energy system. UK Government data assumptions are used across the scenario.

- **High Hydrogen**: Based on the minimally constrained scenario, with a range of constraints added to force hydrogen use across the economy. These constraints are based on estimates of H2 demand ranges in the DESNZ Hydrogen transport and storage networks pathway policy paper[86] published in 2023. A maximum hydrogen consumption in each sector and a minimum overall level of consumption is applied in each year from 2035 to 2050.
- **High Diversification**: Based on the minimally constrained scenario, this scenario aims to be more energy secure through two means, 1) limiting imports of key commodities to reduce UK reliance on overseas resources, and 2) diversifying resource and technology use across the economy to limit the impacts of any supply interruptions, price rises, or technology failures.

For energy storage technologies and energy networks, UK TIMES alone does not provide robust outputs, due to the limited time and spatial resolution of this model. The UK TIMES analysis was therefore augmented with additional model runs with UCL's highRES model, an electricity system optimisation model with an hourly temporal resolution and a spatial resolution consisting of nine UK nodes and nine European nodes (Figure 13), to give insight into the innovation value of these technologies. To ensure consistency with the rest of the EINAs outputs, highRES uses outputs from UK TIMES EINA runs as inputs, including the following:

- Load curves in highRES are based on the degree of electrification of energy service demands, modified to account for likely DSR behaviour.
- The total CO_2 emission limits in highRES are set to the UK TIMES grid carbon intensities.
- Capacities of electricity generation technologies from UK TIMES are used as minimum capacities in highRES.
- Technoeconomic data and innovation assumptions consistent with those used in UK TIMES.

Based on these inputs, highRES co-optimises capacities and locations of the modelled technologies, alongside the build out of additional storage capacity and transmission capacity between zones to minimise the total system cost. All CAPEX costs are annualised based on the respective lifetime of each individual generation, storage, and transmission asset. Limitations in this modelling approach include:

- A simplified network topography with only one transmission line between each zone, limiting costs to a single £/km rate.
- Substations costed at a cost/capacity of network.
- Distribution networks are not included.
- Offshore network not included.

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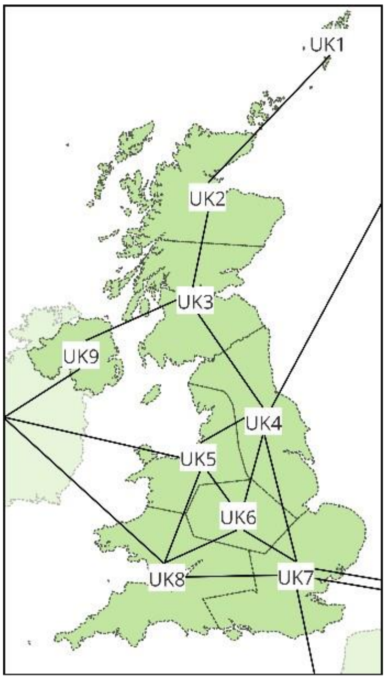
[86] Hydrogen transport and storage networks pathway (GOV UK, Accessed Apr 2025)

Figure 13: Spatial zones for the UK used in the highRES model.



The years 2035 and 2050 are modelled as standalone snapshots for the Minimally Constrained and High Diversification scenarios. High Hydrogen was not run due to limitations on the number of model runs that could be completed within the scope of this project. Each set of runs is carried out for a typical weather year, labelled Average (2012 data), and a poor weather year, labelled Poor (2010 data). A poor weather year represents a year with more periods of low wind coinciding with low temperatures (extreme/less favourable weather for renewable energy generation).

The results presented below demonstrate the potential impact of innovation across all scenarios and innovation levels on the required size of network and associated transmission costs on achieving Net Zero. Whilst model runs are conducted in highRES for each specific storage technology, the EINAs Networks report presents only "All technology" runs, where all EINA technologies are collectively set at a high, medium, or low innovation case. Changing the costs and performance of technologies through innovation can have both direct and indirect consequences:

- Direct consequences are a reduction in cost or an improvement in the quality of the energy service supplied by the technology. Only cost reductions are examined in the UK TIMES energy system model.
- Indirect consequences are changes to the wider system caused by a relative change of cost of a technology relative to other technologies. If a technology becomes increasingly deployed because of reduced costs, and the use of alternative technologies decreases, an overall cost reduction will occur. However, this cost reduction will be less significant than the direct cost savings that would have been achieved if the new technology had been used at lower levels of innovation. More profound changes could also occur across the energy system, for example changes in total electricity consumption or in the relative rate of decarbonisation between sectors of the economy.

We have not considered rebound effects where lower costs of energy due to innovation investments lead to higher energy service consumption. All results are presented as annualised cost figures, in £2022 real values. This differs from UK TIMES results, where cumulative discounted costs can be more easily calculated.

The analysis below refers to only the EINAs technologies. It should be noted that given these results are an output of the system modelling and the three hypothetical scenarios developed for the EINAs that do not necessarily reflect UK government deployment targets and ambitions.

Systems modelling results

In general, the modelled scenarios indicate that increasing levels of innovation across all EINA technologies results in a reduction in the size of required transmission infrastructure, with innovation causing cost reductions of 2 to 8% in the medium model runs, increasing to 6% to 10% with a high level of innovation across the EINAs technologies. The size of transmission capacity required in 2035 ranges from lows of ~105GW in a Minimally Constrained scenario with high innovation in a poor weather year, to highs of ~141GW in a Minimally Constrained scenario with low innovation in a typical weather year (Figure 14). By 2050, the highest transmission capacity required is also observed under a Minimally Constrained scenario with low innovation in a typical weather year, reaching 172GW.

Given the range of required transmission infrastructure is relatively narrow, the network buildout required will remain largely consistent irrespective of generation and storage technology innovation. Consequently, reducing the cost of network build-out through innovation is a no-regrets decision, regardless of the choices and pathways taken in other areas. Similarly, variation between system configuration, or scenario, has minor impact overall, with only slightly higher transmission capacity required in a Minimally Constrained scenario, as a result of generation capacity being further away from areas of high demand.

There is greater disparity in results across scenarios when considering the influence of weather years. In the Minimally Constrained scenario, transmission capacity varies by up to 20% between different weather years, with higher capacity required in an average weather year. The High Diversification scenario is less affected by this variability, showing a maximum variance of only 6%. In poor weather conditions, the need for transmission capacity decreases in part due to the increased deployment of natural gas and hydrogen turbines which can be located closer to demand centres compared to other generation technologies e.g., offshore wind. Consequently, the reduced need to transport renewable generation leads to less transmission infrastructure required, particularly between zones UK2 and UK3.

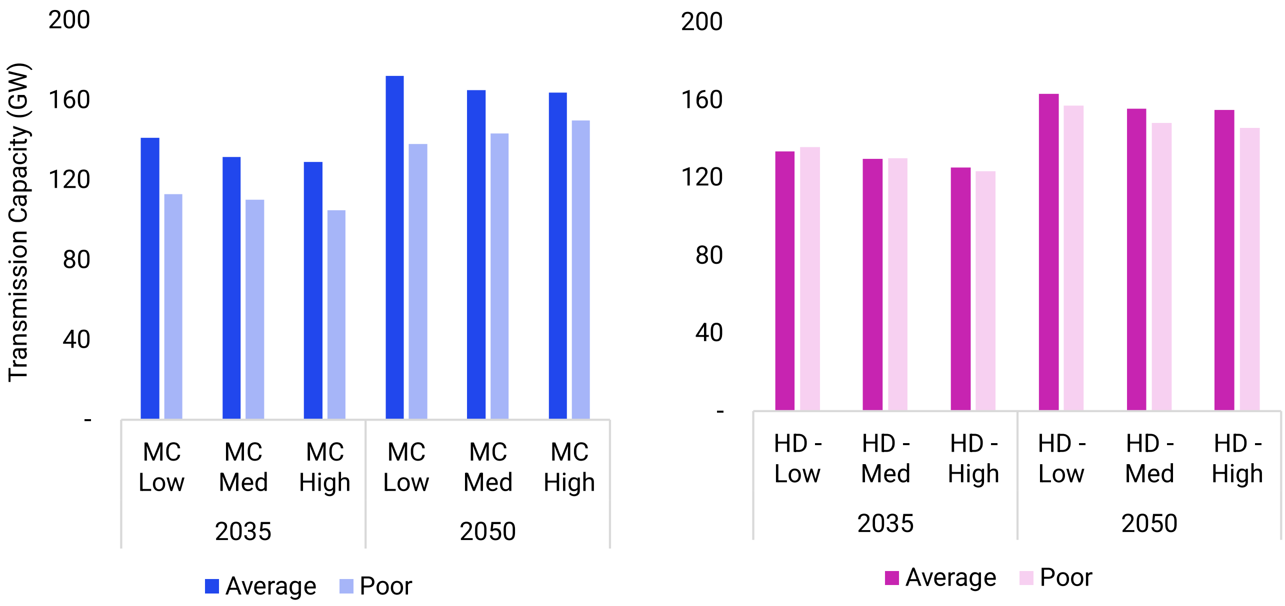


Figure 14: Total transmission capacity in 2035 and 2050, Minimally Constrained (MC) and High Diversification scenarios (GW).

Geographical zones show similar trends to those seen across the overall system. Zones UK2, UK3, and UK4 require the highest capacity in both 2035 and 2050. This is due to the need to transport renewable generation in Scotland (in Zones UK2 and UK3) to demand centres in the south, helping to reduce constraints and meet demand. In poor weather years, this requirement decreases slightly due to higher build-out of thermal generation closer to demand centres.

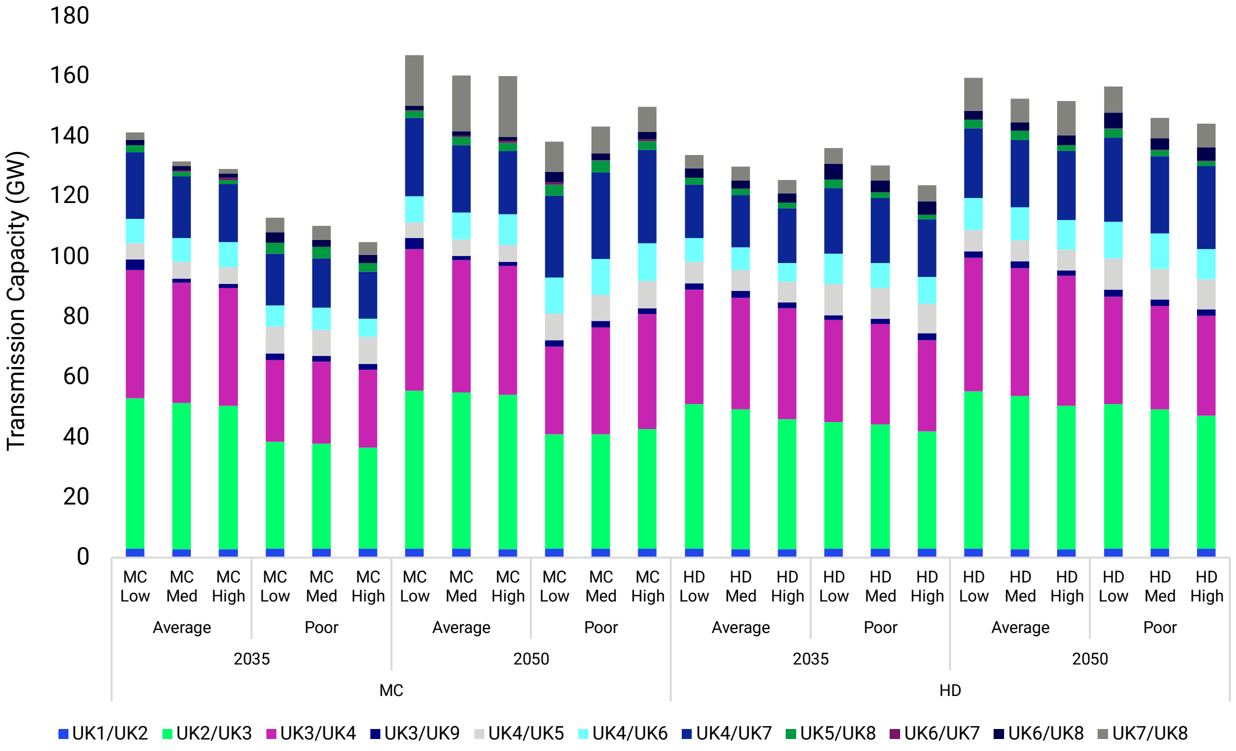


Figure 15: Total transmission capacity between represented highRES zones (GW)

Figure 16 and Figure 17 show that total transmission cost in the scenarios and innovation cases modelled ranges between £1.6 and £2.1 billion in 2050, with the counterfactual baseline showing one of the highest predicted costs. In both the minimally constrained and the high diversification scenarios, model runs for a typical weather year show high innovation is projected to result in the lowest total transmission costs in both 2035 and 2050, with low innovation expected to result in highest transmission costs. High and medium innovation cases exhibit a very close relationship, yielding similar outcomes in both 2035 and 2050.

This trend holds true in poor weather conditions in 2035. However, in 2050 in the minimally constrained scenario only, the reverse pattern is observed, where high innovation levels in 2050 incur the highest transmission cost (~ £1.9 billion). Conversely, a low innovation case in the same scenario exhibits an opposite pattern under poor weather conditions, starting highest in 2035 and lowest in 2050 compared to its respective other innovation cases. In part, this could be due to increased deployment of new natural gas in 2050 in this scenario (poor weather), reducing the transport distances of generation to demand centres and therefore infrastructure need.

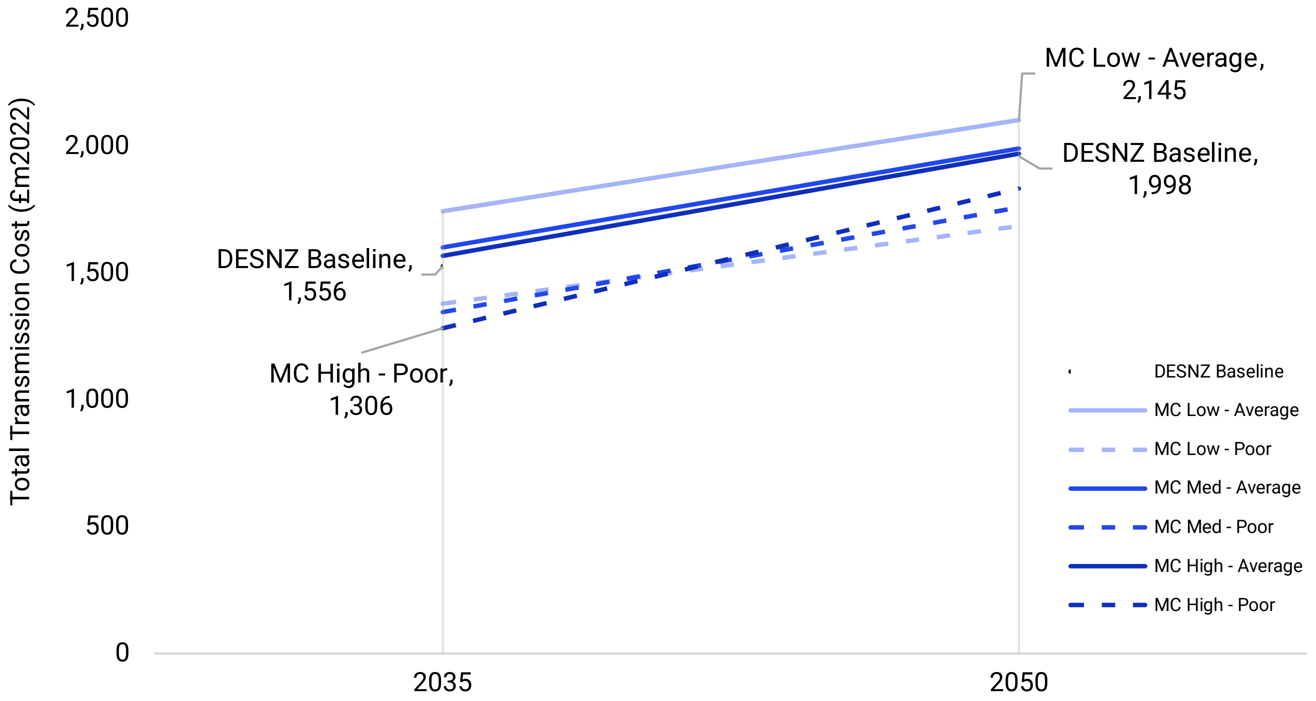


Figure 16: Transmission costs in 2035 and 2050, Minimally Constrained (MC) scenario (£m2022).

Overall, the High Diversification scenario demonstrates less variation across different innovation cases and weather years, due to the higher levels of constraints in this scenario that restrict the location and amount of each type of generation technology.

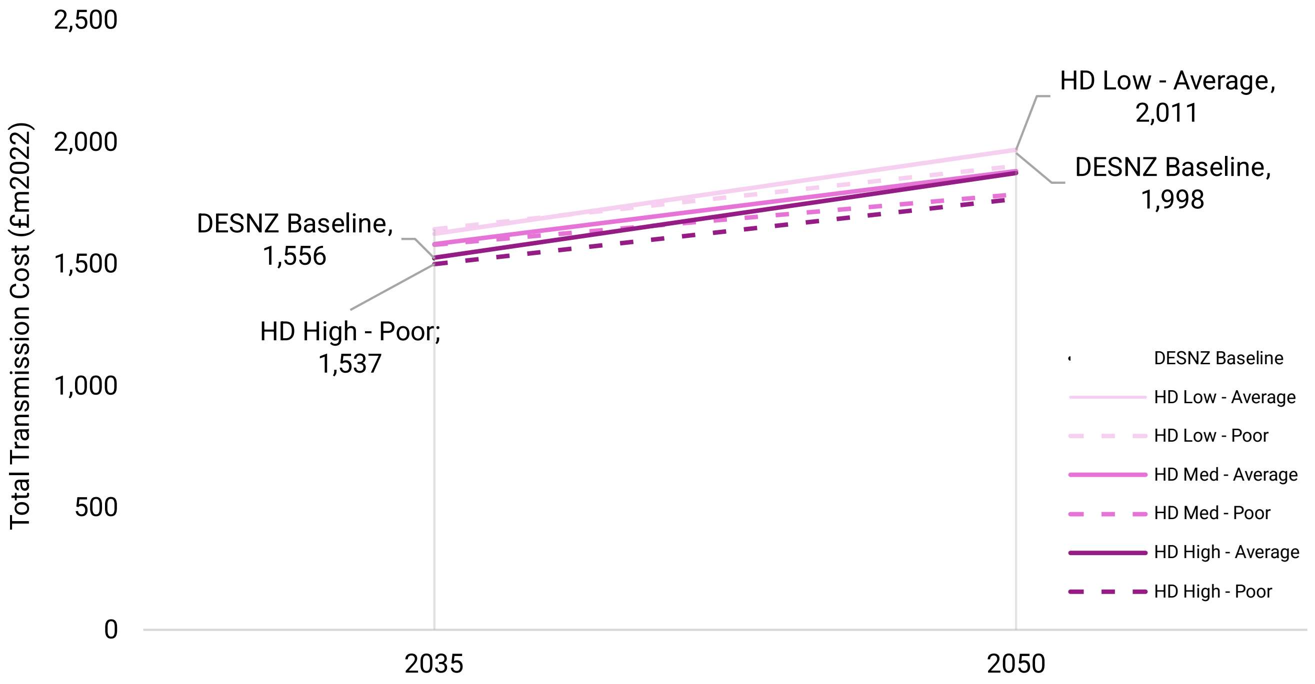


Figure 17: Transmission costs in 2035 and 2050, High Diversification (HD) scenario (£m2022)

Conclusions

The key drivers for UK network innovation are gas decarbonisation, rapid electrification, and the increasing need for advanced digitalisation networks. These drivers necessitate an integrated systems approach to optimise resource use and facilitate the integration of renewable energy sources. The transition to a low-carbon economy places unprecedented strain on the existing energy network, requiring significant upgrades and innovations to meet future demands. High-priority innovation areas where public funding is concerned include, but are not limited to, second-generation cables, HVDC converter hubs, DFTs, DLR, and gas network decarbonisation / decommissioning. These technology areas are essential for enhancing network capacity, improving grid flexibility, and accommodating the growing demand for electricity.

The economic opportunities associated with these innovations have the potential to considerably accelerate Net Zero efforts, both through direct impacts of investments as well as secondary impacts within the wider energy system. The deployment of high-priority technologies such as HTS cables, DLR, and DFTs could contribute significantly to the UK's Gross Value Added (GVA) and job creation. For example, innovation in HTS, dynamic line rating, and distributed feeder technologies could contribute between £0.20bn and £1.15bn in GVA by 2050. This would drive significant improvements in network performance, support broader system development, and stimulate the necessary skilled workforce required.

While clear innovation priorities have been identified, equally important is the adoption of a holistic approach to address the multifaceted challenges of gas decarbonisation, electrification, and energy security. Furthermore, the need for flexible and open innovation pathways is highlighted, given the considerable uncertainty in network transitions. An agile approach to innovation, where system development iteratively shapes network priorities, is essential to navigate these uncertainties. Coordinated efforts between Ofgem, DESNZ, Innovate UK, NESO and other key stakeholders are essential to align innovation initiatives and drive transformative solutions. The establishment of clear regulatory frameworks and supportive policies will be critical in de-risking investments and stimulating market momentum.

In conclusion, the advancement and implementation of these technologies are pivotal in modernising the UK's energy infrastructure and aiding the shift towards a low-carbon economy. By encouraging strategic collaboration among stakeholders and establishing clear policy directives, the UK can foster an environment that promotes innovation while joint efforts and targeted investments in priority technologies offer the greatest potential for rapid progress, leading to significant enhancements in network performance and supporting the overall energy transition.

Appendices

A1 - Sectors and technologies covered in EINAs reports

The EINAs Summary Report provides more clarity of what has been covered across the wider EINAs reports, with dedicated needs assessments on offshore renewables (offshore wind and tidal stream), nuclear fission, heating and buildings, carbon management (CCS, DACCS, BECCS, and geological storage), hydrogen, energy storage, networks (covered in this report), and industry. Refer to the summary report for more detail.

A2 - Longlisted network technology areas

A2 details the initial 12 network technology areas that were used to initiate engagements and further prioritisation of specific network technologies. The table provides examples for each technology area, though it is not an exhaustive list. Technology areas prioritised are highlighted in green, note that the prioritised technology areas evolved from the initial groupings presented below into network outcomes (shown in Table 2).

Technology Category	Technology Area	Technology Area Examples	Innovation Impact
Key infrastructure	Enhanced network capacity	Wireless electricity transmission, high-voltage superconducting transmission cables, HVDC converters and circuit breakers, and LVDC networks.	Unlock better accommodation of increasing energy needs. Reduce curtailment and thermal constraints while allowing for better integration of renewable energy.
	Power electronics (transmission / distribution)	The efficiency, compactness and reliability of power semiconductors for higher voltage and currents. Transistors and diodes, wide bandgap semiconductors, and advanced control and impedance shaping strategies.	Higher level of power processing efficiency. Reduced use of land and resources.

	Applied technologies for energy networks	Robotics, material science, and quantum computing for network optimisation.	Time-efficient automated procedures and reduced running costs if novel materials are used. Ability to model a growing and complex system, better detect faults and load balancing needs which results in improved decision-making.
	Eco-designed energy infrastructure	Energy infrastructure designed and constructed with a minimal environmental footprint, less energy-intensive production methods with minimised waste. Asset recyclability, repairability, and end-of-life e.g. Predictive maintenance in smart grids which uses sensors and analytics to predict failures, in turn, reducing downtime, energy losses and extends asset lifespan.	Enhances grid resilience, reduces environmental and carbon footprint.
	Grid forming technologies	Approaches that enable inverters and other power electronics to play a critical role in shaping and maintaining the stability of the grid. Virtual synchronous generators, virtual synchronous machines, virtual oscillator control, and virtual inertia control.	During blackouts or grid failures, grid-forming technologies can operate in island mode, supplying power to critical loads. Likely to play a role in inertia services as we decarbonise the grid.

Digital processes	Control systems and digitalisation	Embedded computers, edge and cloud solutions, augmented reality, machine learning, and digital-twin technologies.	Help to obtain optimal system operation through even higher controllability. Improved customer experience of serviceability will be achievable and new concepts of training and safety assurances can be tested.
	Data analytics	Grid state estimation, demand forecasting, consumer preference analytics, and novel tariff design.	Enhance the grid's adaptive response and gives utilities the ability to encourage consumers to reduce usage during peak hours, reducing grid strain.
	Process-based innovation	Connection process digitalisation, improvements in civil work, and better consenting processes.	Unlock faster deployment and upgrades of infrastructure, cost-efficiency, and attract investment - encouraging innovation.
General network innovation	Cybersecurity and cyber-physical systems	Quantum cryptography, information sharing, and AI powered systems.	Optimised energy production, improved real-time monitoring of systems, and more accurate and secure energy flow adjustments.
	Integrated energy systems	Multi-vector systems for generation, charging, etc.	Diversifying energy sources enhances system resilience against disruptions. Improves efficiencies through ‘smarter’ data streams.

	System resilience	Black start capabilities, advancing fault identification techniques, and micro grids.	Enhanced black start capabilities further reduce downtime and therefore less impact on consumers. Advanced fault identification techniques minimise time needed for repairs and accurately targets where repairs are required. Micro grids reduce dependence on the grid and can be islanded, in turn, increasing community resilience.
	Supply chains	Infrastructure supply chain issues (cross-cutting in other technology areas). Digital supply chains.	Beyond the more obvious issues around blockages in supply chains, specific consideration to digital supply chains improve demand-side management including load shifting and peak shaving.

A3 - High priority technologies in scope

A3 highlights the high priority technology areas and provides a definition of sub-technologies falling within the scope of this work. High-priority technologies / network innovation areas with primary innovation needs / gaps. Although these technologies are classified as high priority in this report, there are many other technology areas (covered in the medium / low priority list in A4) of importance. However, this work identified that strategic investment in these might not have the same level of impact owing to risk and technology or market readiness and have therefore been deprioritised for this report.

Technology Area		Key technologies in scope
Enhanced network capacity	Second-generation cables	Focused primarily on High Temperature Superconducting cables in this work (HTS). Other technologies include high-emissivity cables.
	HVDC converter hubs	HVDC converter stations
	Distributed feeder technologies	Distribution Static Synchronous Compensator (D-STATCOM), Distributed Soft Open Point (D-SOP), Distributed Smart Transformer (D-ST)
	Dynamic Line Rating (DLR)	Dynamic line rating (or real-time thermal rating)
	Subsea cables	Extra high voltage (EHV) DC mass impregnated subsea cables
Digitalised control systems and ‘smart’ networks	Advanced next-generation dispatch algorithms	As with DLR, control and dispatch innovation requires the ability to process vast amounts of data from various sources (smart meters, weather forecasts, grid sensors etc.), to optimise energy dispatch in real-time
	Critical AI tools for networks	AI tools for networks (e.g., Surrogate Machine Learning Models; Generative AI; Neuro-symbolic AI)
Cybersecure networks	Quantum encryption and cryptography	Quantum VPNs and other quantum-safe encryption technologies
	Islanded architecture of critical infrastructure	Cyber-physical architecture (communication and network technologies / typologies)

Resilient and climate-ready networks	Grid-forming technologies	Grid forming inverters providing inertia and frequency regulation
	Gas network repurposing	This category was less around specific technologies and more related to the whole-system coordination around various actors to decarbonise and decommission gas networks.

A4 - Medium-Low-Priority technologies considered

A4 summarises other key technologies considered, but not taken forward for further analysis, in this assessment.

Technology area	Technology
Cybersecure Networks	Digital twin of networks as a testbed for controlled hacking to identify weak and vulnerable spots
	Early demonstration of quantum computing with other high-performance computers for network optimisation (hybrid approach)
	Blockchain for distributed information and/or contracting.
	Improved system modelling such as understanding the topological interdependence between cyber-physical systems of heterogeneous networks
Digitalised Control Systems and 'Smart' Networks	Advanced computing processes (neuromorphic / exascale / edge computing)
	Augmented reality (AR) for training (construction, control rooms)
	Automated drones dispatch for data collection (grid periphery / rural)
	Data management systems such as data cooperatives and data fabrics (the automation of a data pipeline)
	Improved digital twins to model larger geographies and provide better geospatial planning
	Large-scale demonstration of local-scale smart systems with a focus on validating dispatch / control algorithms.
	Self-healing / -optimising systems for LV networks

	An open, cybersecure digital platform owned by National Grid for energy networks which will allow all data and modelling across the system to be compatible
	Better control systems and software for community level trading (Peer-to-Peer)
	Devices to make assets data-ready for flexibility automation and monitoring
	Improved digital twins to model more complex climate scenarios on networks
	Improved network controls at the EV fleet level
	Infrastructure to make an offline and real-time simulation environment around critical infrastructure (HVDC etc.)
	Large-scale monitoring demonstration on live assets to simulate control scenarios
	Optional EV charging to avoid system overload of demand on system
	Remote methane leak monitoring (satellites) to support gas pipeline repurposing
	Technology for better signal quality degradation
Enhanced Network Capacity	Advanced algorithms for continental-scale ancillary services
	Integrated electricity-gas operations
	Modular-Static Synchronous Series Compensators (m-SSSC)
	Retrofit Insulated Cross Arms (RICA)
	Advancing on-the-ground network infrastructure to make it physically able to receive space-based solar power
	Electrolysis waste-to-heat technologies for district systems / storage
	Regional cold start technologies
	Space-cooling technologies - e.g., solar powered fans/ACs as cooling demand will be highest in the sunnier months.
	Transmission infrastructure for floating offshore wind

Resilient and Climate-Ready Networks	Underground cabling robots
	Climate resilient critical infrastructure to withstand extremes
	Super conducting fault-current limiters
	Fibre optics for network redundancy
	Increasing redundancy in the system through satellite infrastructure centres
	Repurposing of legacy technologies such as long range radio (LORANG) for system resilience
Sustainable and Secure Supply Chains	Digital data platform for supply chains to enable actors to have better visibility around critical infrastructure.
	Future semiconductors (new materials e.g., compound semiconductors)
	Improved recycling of critical and rare minerals (e.g., those used in rare Earth magnets in EVs and wind turbines)