Guidehouse
Outwit *Complexity*

Gas and Electricity Transmission Infrastructure Outlook 2050

Final report

March 2023

Foreword

The Gas and Electricity Transmission Infrastructure Outlook 2050 is the result of a joint collaboration between National Grid Electricity Transmission, National Gas Transmission and National Grid ESO. This study explores the development of an integrated energy infrastructure for Great Britain to achieve its 2050 net-zero target whilst reducing costs to consumers and maintaining energy security.

Great Britain is on a mission to achieve net-zero by 2050. The energy transition requires us to re-think the way we develop and operate the energy system and its infrastructure. A coordinated gas and electricity transmission infrastructure outlook is the first step in achieving that objective.

One of the key messages from this study is that across all the modelled scenarios integrated electricity and hydrogen transmission infrastructure planning can realise savings, especially in System Transformation where energy system savings of £38 billion by 2050 are possible. Early investments common across the transmission networks are needed to realise these savings.

It has been recognised by Ofgem and government that a whole energy system approach to system planning will be part of the Future System Operator remit. To realise this in the most cost-effective way, the energy system will however need to address some evident gaps, which this work takes a key step in identifying.

Further leadership and collaboration, appropriate incentives and infrastructure investments are essential for Great Britain to achieve whole energy system planning and realise its considerable benefits.

national gas transmission nationalgrid ESO

Agenda

Executive Summary

Introduction

Methodology

Results

- Electricity
- Hydrogen

Sensitivity Scenarios

Conclusions

Executive summary

Across **all the modeled scenarios integrated electricity and hydrogen transmission infrastructure planning can realise savings,** especially in **System Transformation** where energy system **savings** of **£38 billion by 2050** are possible. Early investments common across the transmission networks are needed to realise these savings.

Executive summary

In an integrated electricity and gas system,

- Introducing **electrolysis** to the energy mix has the potential to greatly **reduce renewable generation curtailment**. Other technologies could have a similar impact.
- Maximising renewable generation on the system is key to meeting UK net-zero ambitions. This requires an increase in the **importance of dispatchable peak supply** and of demand-side flexibility resources.
- In the project scenarios **storage plays a key role with hydrogen**, among other solutions, **being a highly viable solution during low-wind periods** by providing non-intermittent supply to support both gas and electricity systems.

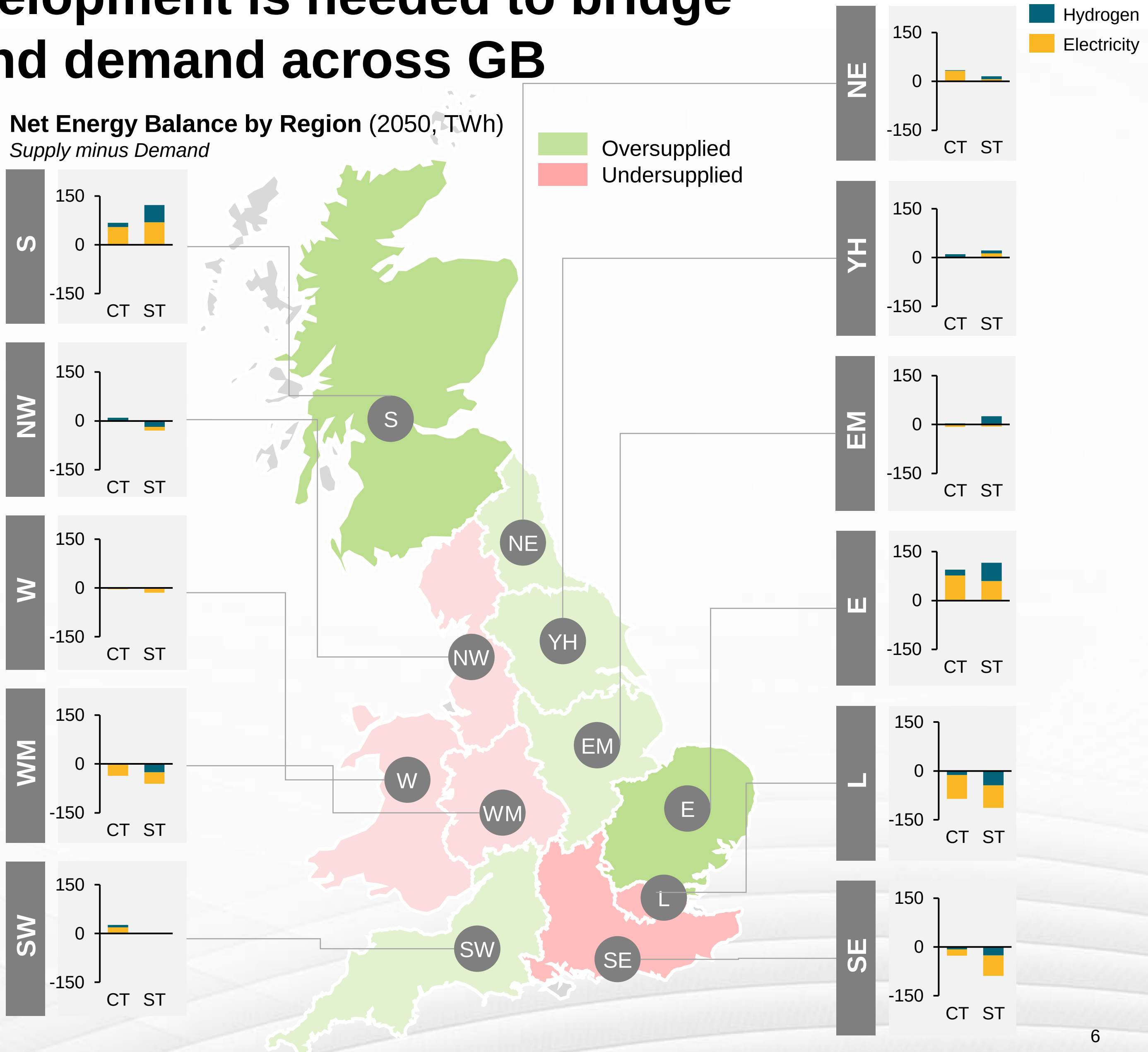
Transmission infrastructure development is needed to bridge regional differences in supply and demand across GB

Key Messages

- In 2050, there would be **significant differences in the electricity and hydrogen supply-demand balance** across GB.
  - Our analysis shows a significant **North-South imbalance** in energy supply and demand, as well as an **East-West imbalance**.
  - Regions in the North and East benefit from **abundant renewable energy potential**, while other regions may require electricity and hydrogen imports to meet their demand.
- These **regional energy supply-demand differences are consistent** to a great extent **across different visions of the future** (CT and ST scenarios).

Transmission infrastructure is needed to connect electricity and hydrogen supply and demand across GB

Net Energy Balance by Region (2050, TWh)
Supply minus Demand



Strategic investments in electricity and hydrogen infrastructure could reduce total energy system costs by an estimated 10%

Key Messages

- In **an integrated transmission system,** electricity and hydrogen transmission infrastructure is sized to allow energy supply to serve both electricity and hydrogen demand;
  - **This optionality requires additional upfront investment in transmission infrastructure**
- However, an integrated transmission system enables **supply capacity** to be **optimally sized and located** to serve both electricity and hydrogen demand.
  - **This results in avoided investments in more costly energy generation infrastructure**

Investing in developing an integrated transmission system delivers whole energy system savings, as investments in transmission infrastructure capacity are less costly than generation capacity investments

Compared to an energy system with limited integration, an integrated energy system (used FES2022 System Transformation as an example) could result in:

+£5 billion
more investment in transmission infrastructure

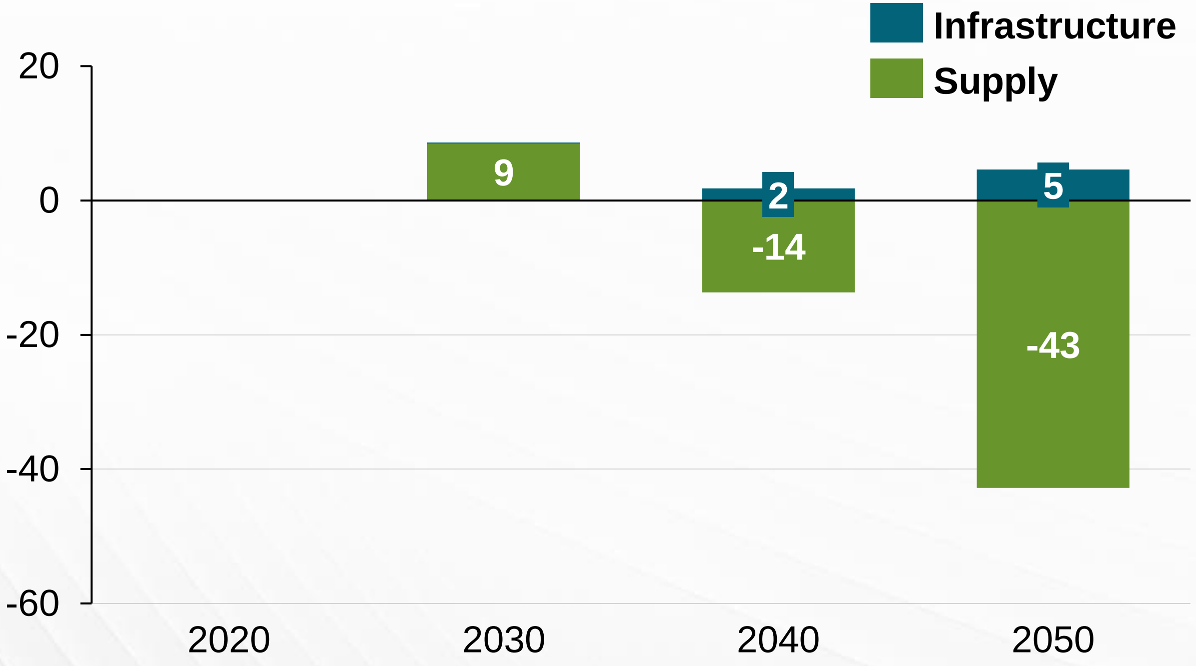
-£43 billion
less investment in energy generation

Up to £38 billion
(or ~10% savings)
of energy system savings in an integrated system

Long-term, whole system planning delivers long-term benefits, even if that increases costs in the near-term

Long-term strategic investments are key

Cost Difference in Total Energy System
System Transformation vs Limited Integration
(Cumulative £ billion)



Key Messages

- **An optimised integrated whole energy system is likely to increase costs in the near-term** as supply capacity scales up rapidly to accommodate for a not-yet fully optimised energy system.
- There needs to be a **focus on long-term whole system planning to identify strategic investments** that can significantly **drive down cost for consumers** in the future.
- Integrated, transmission whole-system planning delivers infrastructure optionality and can help de-risk new projects, increasing the likelihood of investments.

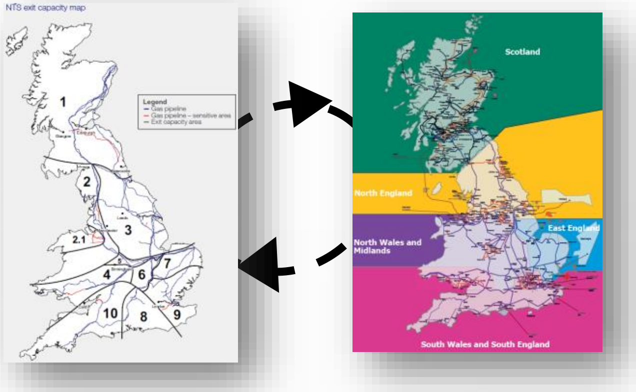
Note: *Higher system costs in 2030 are* ***NOT*** *linked to investments timings, they are purely the results of a momentarily sub-optimal system.*

This study explores the benefits of whole system planning in Great Britain to help guide the development of effective market and policy frameworks

Aim and Vision

"Whole system planning is key to achieving the most cost-effective transition to net zero, whilst maintaining security of supply throughout. A coordinated gas and electricity infrastructure outlook is the first step in achieving that objective."

This project will help identify gaps in policy, market and regulatory frameworks to realise the benefits of a more integrated and optimised system for future gas and electricity transmission, delivering Net-Zero energy to all sectors.



Modelling output combined with stakeholder engagement will support policy and regulatory dialogue and an innovation project pipeline ***involving and benefiting all Great Britain's Energy Sector Stakeholders while delivering the optimal energy system for consumers***

To assess the value of whole system planning, this analysis uses an integrated capacity expansion and dispatch optimisation model

General Model Configuration

- This study uses Guidehouse’s Low Carbon Pathway (LCP) model to simulate the **decarbonisation of the electricity and gas system from 2020 to 2050 in different scenarios.**
- The model is configured to a **geographical scope made of 23 sub-regions** within GB, offshore nodes and neighboring regions (Ireland, Western Europe and Northern Europe) and **models an integrated electricity, hydrogen and methane system.**
- **The modelling methodology section describes, in more details, the LCP model, its configuration, operation and limitations.**

Study Configuration

23x Geographic Scope:

- ➢ 11 GB regions
- ➢ 9 offshore nodes
- ➢ 3 neighbouring regions

4x Model Years:

2025, 2030, 2040 and 2050

6x Rep. day:

Spring Summer Fall Winter Winter Peak Winter Peak & No wind

3x Scenarios:

Net-Zero FES:
-Consumer Transformation (CT)
-System Transformation (ST)
-Leading The Way (LW)

2x Sensitivities:

-GB as a hydrogen exporter
-Change in hydrogen storage
-Limited Integration counterfactual

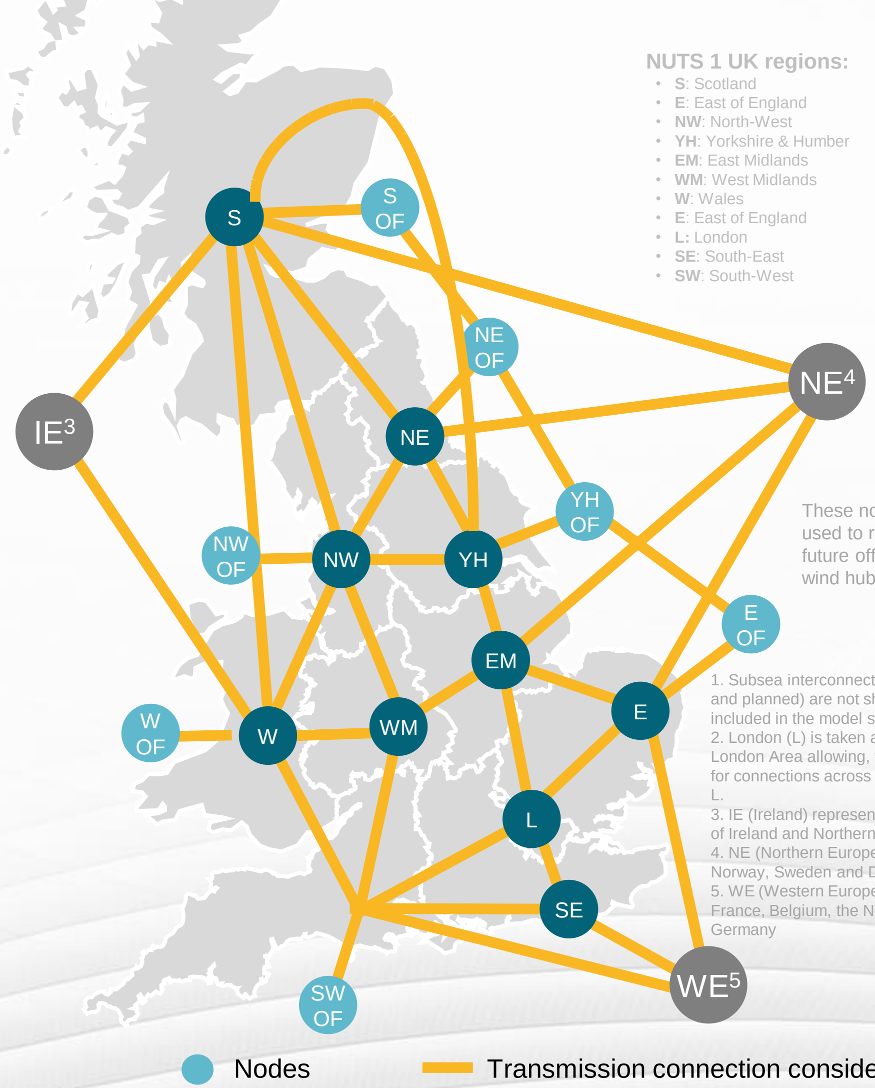
3x Energy Carrier:

Electricity
Hydrogen
Methane

24x Timestep:

Representative days
Hourly profiles

Model Nodal Configuration



NUTS 1 UK regions:

- **S**: Scotland
- **E**: East of England
- **NW**: North-West
- **YH**: Yorkshire & Humber
- **EM**: East Midlands
- **WM**: West Midlands
- **W**: Wales
- **E**: East of England
- **L**: London
- **SE**: South-East
- **SW**: South-West

These nodes are used to represent future offshore wind hubs

1. Subsea interconnections (existing and planned) are not shown but are included in the model setup.
2. London (L) is taken as the Greater London Area allowing, for example, for connections across EM-L and SW-L.
3. IE (Ireland) represents the Republic of Ireland and Northern Ireland.
4. NE (Northern Europe) represents Norway, Sweden and Denmark.
5. WE (Western Europe) represents France, Belgium, the Netherlands and Germany

Note: Modeling limitations are discussed in D1.5

The analysis uses National Grid's Future Energy Scenarios (FES) as the basis for modelling different whole system scenarios

How are these scenarios used and what is the value to the study

This study uses these scenarios to fix parameters such as demand, nuclear capacity or demand-side flexibility. **The FES scenarios provide a framework** to ensure that the inputs in this study are **realistic and aligned with the current system thinking.**

Throughout all scenarios, the model optimise a gas and electricity integrated system. As a counterfactual to this, the next section compares this optimisation with a non-integrated System Transformation scenario, to highlight the benefits of the integrated approach to whole system modelling

System Transformation (ST) and Consumer transformation (CT) provides two opposite visions for the future net-zero energy system in GB. **Comparing these two visions allows to identify differences, but most importantly, similarities in the modelling results.**

FES Scenario narrative reminder

Consumer Transformation

- Electrified heating
- High level of consumer engagement (V2G, DSR, etc.)
- High energy efficiency
- Higher peak electricity demands

Leading The Way

- Fastest credible decarbonization
- Significant lifestyle change
- Mixture of hydrogen and electrification for heating
- Highest levels of demand-side flexibility

System Transformation

- Hydrogen for heating
- Consumers less inclined to change behavior
- Lower energy efficiency
- Supply side flexibility through hydrogen production

Source: Future Energy Scenario (FES) 2021, National Grid ESO

Methodology and approach

Agenda

- General Methodology (incl. limitations)
- Modelling configuration

This study aims to develop an objective and analysis-based view of a more integrated, net-zero energy system by 2050

Project Context

- National Grid Electricity Transmission, National Gas Transmission and Electricity System Operator commissioned a study to create **an objective and analysis-based vision** of a whole energy system that addresses the interactions and complexities of an integrated electricity and gas energy system.

Why a "whole system" approach?

- A whole system modeling approach recognises that analysing the electricity and gas systems in isolation is not sufficient, nor appropriate. This is particularly important in the context of the electricity and gas systems becoming increasingly interdependent in the pathway to net zero.

  For example, electricity networks will have to be sized and will have to account for generation capacity fully or partially dedicated to the production of hydrogen. At the same time, gas networks will have to be repurposed to accommodate increasing volumes of hydrogen flowing through the network as well as the use of hydrogen in power generation.

What are the benefits of a "whole system" study?

- Implementing a whole system approach will highlight key areas where increased interaction between electricity and gas infrastructure will be required and where changes to regulation, market frameworks and system operator practices may deliver value to consumers.
- Since National Gas Transmission (NGT), National Grid Electricity Transmission (ET) and Electricity System Operator (ESO) represent different system perspectives – it is crucially important that all three entities are equally involved, heard and engaged. This ensures that this study is built on internally-consistent scenarios and views how the energy system will evolve towards a net zero 2050.

Connection to FES

- This study seeks to expand on the work performed by National Grid ESO on its Future Energy Scenario (FES). The FES acts as a foundation to this analysis by serving as its basis for future scenarios of energy demand.

- The FES's three net-zero scenarios – System Transformation (ST), Consumer Transformation (CT) and Leading the Way (LW) – provide three different, but plausible visions of future electricity, hydrogen and methane demand and supply. The FES analyses these three scenarios from a broadly top down GB-level perspective of supply and demand rather than on a full and explicit bottom-up regional basis. It also assumes an unconstrained network so as not to bias downstream network development activities.

- In this study, we expand on these three FES scenarios by disaggregating energy demand across each of GB's 11 NUTS1 regions. **This regionalisation approach is described in slides 14-16.** We then apply a whole system approach to explore implications on the buildout and localisation of electricity and gas resources, as well as implications on the buildout and operation of electricity and gas transmission infrastructure.

- This analysis does not adopt all the views of the FES on future electricity and gas supply. However, on occasion, it adopts certain supply assumptions that are tightly aligned with the spirit of each FES scenario. **These exceptions are also described in slides 14-16.**

Analysis Considerations and Limitations

- This reports presents a large set of detailed assumptions and inputs that will be used to model the GB electricity and gas system. While this study aims to adequately simulate the operation and evolution of GB's electricity and gas systems - a system made up of GB's 11 NUTS1 regions and three (3) neighboring regions (Ireland, Western Europe and Northern Europe) – the results of this analysis are not intended to dictate when and where supply and transmission infrastructure investments may take place.
- The results of this study will be purely **reflective of an economic, cost-optimisation exercise**, and does not reflect specific technical, operational and locational (spatial) constraints of GB's electricity and gas system. Investments in supply and transmission infrastructure are, naturally, contingent on energy policy, regulation and strategy. Future findings from this study should be read in this context and should take into consideration limitations of the analysis.
- This study does not consider outputs from other ongoing projects / other models that may have been developed over the course of the project e.g. Project Union, Holistic Network Design.

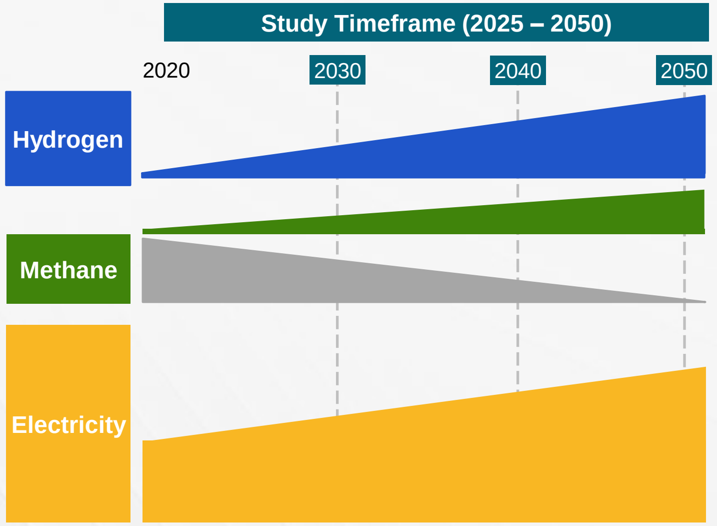
General Methodology

We approach scenario development taking demand from FES net-zero scenario and modelling energy supply and infrastructure

Energy Demand

We disaggregate hydrogen, methane and electricity demand from the three FES net-zero scenarios across each of GB's 11 NUTS1 regions. **The next slides describe these regionalisation approaches in detail.**

- **Hydrogen**: We apply a sector-specific approach, using FES and other secondary resources, to disaggregate hydrogen demand across NUTS1 regions.
- **Methane**: We disaggregate methane demand across NUTS1 regions using historical, regional gas demand by LDZ[1]. We also make regional demand adjustments to account for only some regions having material biomethane supply potential.
- **Electricity:** We determine the regional distribution of electricity demand using GSP-level FES results[2] – which account for approximately 85% of total customer demand – and apply that distribution to the total electricity demand.



11 NUTS1 regions

Energy Supply and Infrastructure

- We define our proposed modeling approach for all major energy supply resources and infrastructure options. This includes electricity and gas supply resources like offshore and onshore wind, solar, nuclear, green gas, or electrolysers, as well as infrastructure options like hydrogen imports, hydrogen transmission infrastructure, or the development of an offshore electricity transmission network.
- In some cases, our approach is to align with assumptions from the FES and, thus, adopt exogenous inputs into our analysis. While for others, our approach is to remain agnostic and endogenously model those technologies / options / decisions.
- **The next slides describe our proposed approach for each of these major energy supply and infrastructure options.**

Offshore Wind
Other Renewables
Nuclear
Hydrogen Supply
Electro -lysers
Green Gas
Hydrogen Imports
Hydrogen Network
Hydrogen Storage
Electricity Interconnections
Offshore Trans. Network
Dispatchable Generation
Electricity Storage
Flexibility & Embedded Generation

1. LDZ = Local Distribution Zone
2. GSP = Grid Supply Point.

Electricity demand regionalisation - We use GSP-level FES results and apply that distribution to the total national electricity demand

Electricity demand regionalisation

BUILDINGS

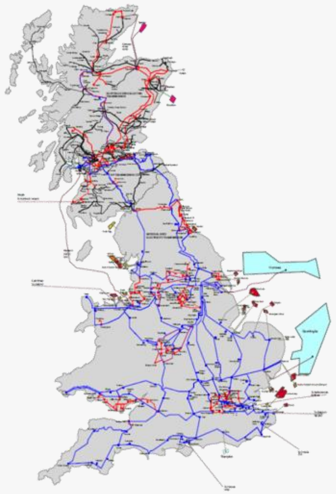
INDUSTRY

TRANSPORT

Note: As part of the ENA's DFES initiative, the FES reports electricity demand and embedded generation at the GSP-level for each scenario. This data is referred to as the "building blocks" of electricity demand. GSP-level data does not capture total customer demand. It reflects the net-impact of embedded generation and excludes transmission-connected loads and demand from rail. T&D losses are also excluded.

- We first aggregate GSP-level electricity demand and embedded generation to each of the 11 NUTS1 regions (e.g., GSP #1, 2, 3, 4, etc. are mapped to Scotland, GSP #5, 6 and 7 are mapped to London, GSP #8, 9, 10 and 11 are mapped to Wales, etc.).
- We add NUTS1-level electricity demand and embedded generation and develop regional shares (%).
- We apply these regional shares to the total customer electricity demand (which includes transmission-connected load and rail).

~350 GSPs



Considerations

- GSP data **nets off** embedded generation
- GSP data **excludes** Tx-connected demand
- GSP data **excludes** rail electricity demand
- GSP data **excludes** T&D losses[1]

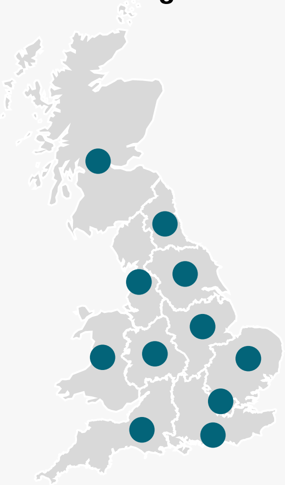
Adjustments

- **Add back in** embedded generation

Implied Assumptions

- Assume Tx-connected demand is **proportionally distributed** across NUTS1 regions.
- Assume rail electricity demand is **proportionally distributed** across NUTS1 regions.

11 NUTS1 regions



General Approach

End-User Demand by GSP (TWh) by GSP

+

Embedded Generation (TWh) by GSP

End-User Demand + Embedded Gen. (TWh) by NUTS1

Note: End-User demand and embedded generation accounts for c.95% of demand. This excludes transmission-connected loads and rail. To apportion these across all regions, we use the regional mix of end-user demand and embedded generation.

NUTS1 share of Demand (%) by NUTS1

×

Total Customer Electricity Demand (TWh) by NUTS1

Sources

- **National Grid FES** (incl. building block data)

1. LDZ = Local Distribution Zone
2. GSP = Grid Supply Point.

Hydrogen demand regionalisation - We apply a sector-specific approach, using FES and other secondary resources to regionalise at NUTS1 level

Hydrogen demand regionalisation

General Approach

Sources

BUILDINGS

- We apply regional shares based on heating equipment stock forecasts from the FES Regional Heating Model (with results available at the Local Authority-level) aggregated up to individual NUTS1 regions.

NUTS1 share of H2 heating equipment (%)

✖

Building H2 demand by scenario (TWh)

- **H2 equipment shares**: FES Regional Heating Model
- **Hydrogen Demand**: Results from each FES scenario

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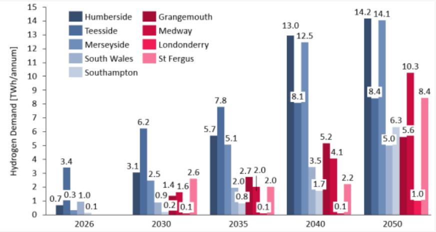
- We apply regional shares using the cluster demand data from the CCC UK industry report up to the total demand outlined in the report (72.3TWh)
- For FES scenarios with higher 2050 H2 demand than the one outlined in the report, the remaining demand is distributed evenly across all regions.



NUTS1 share of H2 demand (%)

✖

Industrial H2 demand by scenario (TWh)

- **H2 demand shares:** Element Energy, Net Zero Industrial Pathways (NZIP) model (Balanced Scenario)
- **Hydrogen Demand**: Results from each FES scenario

TRANSPORT

- **Road**: We apply regional shares based on DfT historical statistics on licensed vehicles.
- **Shipping**: We apply regional shares based on DfT historical statistics on freight tonnage traffic by port.
- **Aviation**: We apply regional shares based on DfT historical statistics on air traffic passenger volume by airport.
- **Rail** demand is distributed proportionally (to the rest of the demand) across all regions

NUTS1 share of transport sub-sector metric (%)

✖

Industrial H2 demand by scenario (TWh)

- **Road transport:** Historical Vehicle Licensing Statistics. Department for Transport, (2022).
- **Shipping**: Historical Freight tonnage traffic. Department for Transport, (2022).
- **Aviation:** Historical Air Traffic at UK airports. Department for Transport, (2022).

General Methodology

Methane demand regionalisation - We disaggregate methane demand across NUTS1 regions using historical, regional gas demand by LDZ.

Methane demand regionalisation

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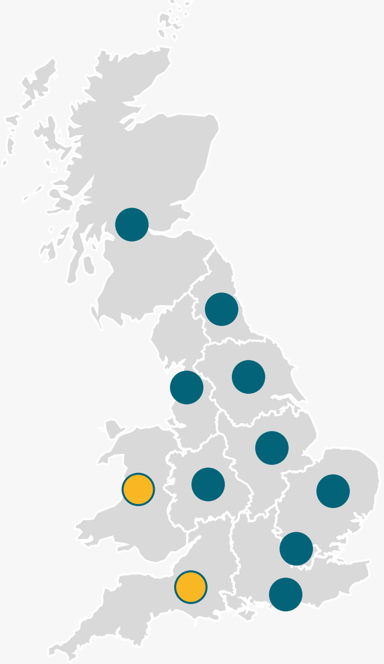
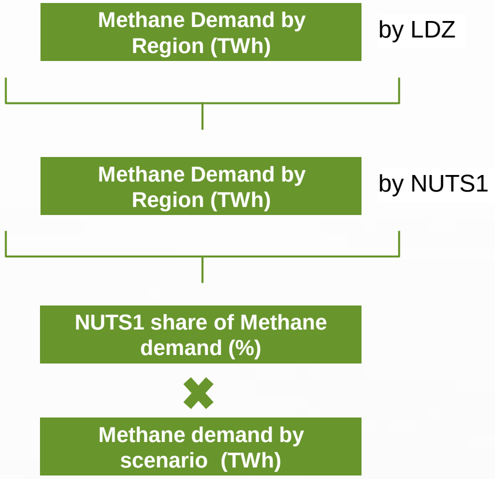
- We use historical (2018-19) subnational gas demand by NUTS1 region shared by BEIS as they excluded gas used for power consumption and match the FES data for the reference year.
- We use these historical gas demand figures to develop regional shares (%).
- We apply these regional shares to the **2030** methane customer demand figures

- For methane demand in **2050**, we assume all demand is distributed across Wales (W) and the South-West (SW) given that these are the only regions with material biomethane supply potential and given that methane transport across regions in 2050 would be unlikely given the repurposing of the gas network to hydrogen.
- For methane demand in **2040**, we take a different approach for W and SW, compared to all other regions. For W and SW, we assume methane demand is the average of 2030 and 2050 demand. We assume the residual methane demand (e.g., total methane demand less demand from W and SW) is distributed across all other regions – in proportion to the regional shares estimated from historical gas demand.

11 NUTS1 regions



General Approach



Note: We apply a different approach to estimate methane demand by NUTS1 region in 2030, 2040 and 2050.

Sources

- **2018-19 hourly gas demand by LDZ-level** (shared by NGT)

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Modelling Configuration

The LCP model is a capacity expansion and dispatch optimisation model adapted to the characteristics of GB’s gas and electricity infrastructure

Overall Approach

- This study uses Guidehouse’s LCP model to simulate the decarbonisation, expansion and hourly optimisation of the electricity and gas system from 2020 to 2050.
- The model is configured to a geographical scope made up of GB, its sub-regions and its neighboring regions (Ireland, Western Europe and Northern Europe) and models an integrated electricity, hydrogen & methane system.
- The analysis models different scenarios of how electricity and gas supply and infrastructure can meet energy demand. This includes identifying what investments in electricity, hydrogen and methane supply capacity and infrastructure will be required, where those investments will be needed, and when they will be needed.
- Approach is based on whole system / multi-vector modeling, and thus outputs would differ from other single vector studies.

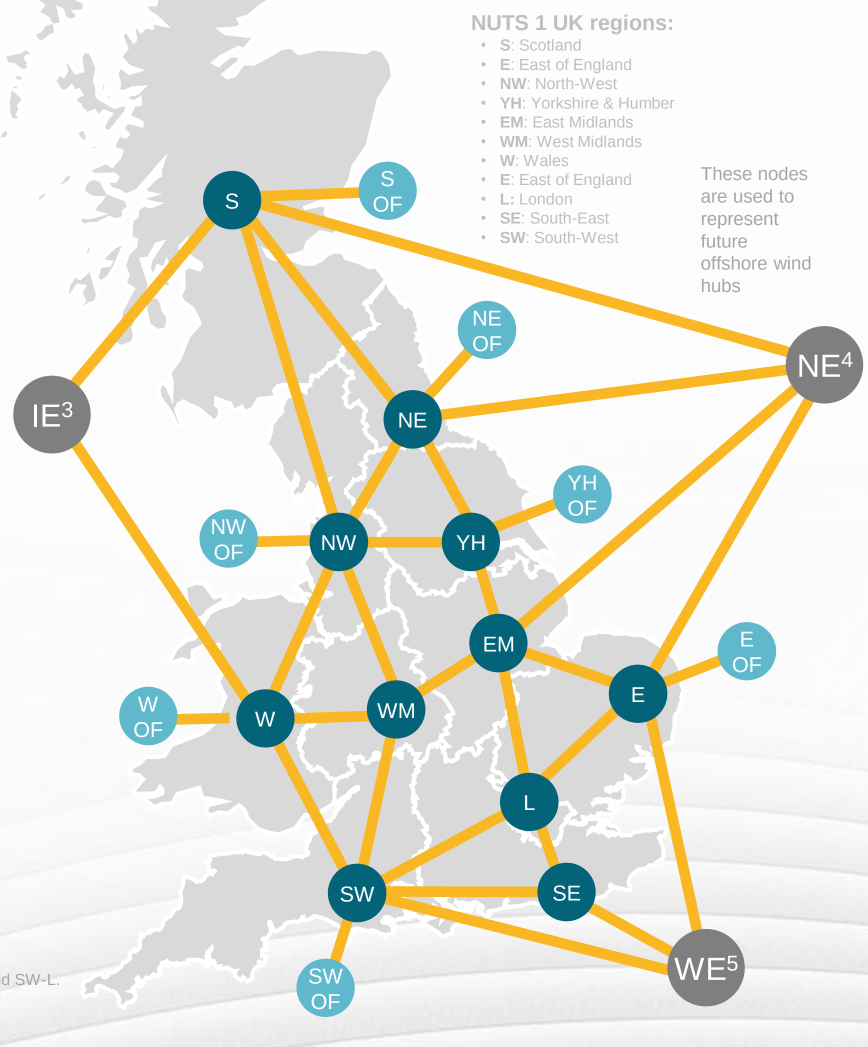
Modeling Configuration

- **Geographic Scope**: 11 GB sub-regions + 7 offshore nodes + 3 neighboring regions. The neighboring regions include:
  - **Ireland:** made up of the Republic of Ireland and Northern Ireland
  - **Western Europe:** made up of France, Belgium, the Netherlands and Germany
  - **Northern Europe:** made up of Norway, Sweden and Denmark
- **Energy carriers**: Electricity, hydrogen and methane
- **Simulation timeframe**: 2020, 2030, 2040 and 2050
- **Intra-annual temporal resolution**: 6 representative days (4 seasonal days, a winter peak-day, and a winter supply/demand extreme)
- Model does not include holistic network design or coordinated approach to renewable integration

Integrated Energy System Modelling

- The LCP model is an integrated capacity expansion and dispatch optimisation model used to identify the lowest-cost pathway to a decarbonise energy system.
- The analysis *solves* the expansion and decarbonisation of the electricity and gas (hydrogen and methane) system by investing in new supply and transmissions infrastructure over time (e.g., onshore wind, offshore wind, solar, electrolysers, hydrogen pipeline, transmission lines, etc.).
- As a “whole of system” model, the cross-sector energy conversion interactions between electricity, hydrogen and methane are an integral part of the analysis (e.g., electrolysers driving increased electricity demand, hydrogen gas turbines driving increased hydrogen demand)
- The analysis also models the use of transmission interconnections across regions (e.g., power lines and pipelines) and storage assets (e.g., gas and electricity storage) to balance supply and demand.
- The analysis’s nodal configuration – whether sub-regions within the core geographical scope or with neighboring regions – defines whether electricity and gas interconnections exist across regions.
- Each node is treated as a “copper plate” of demand and supply meaning there is no sub-nodal granularity of transmission or distribution infrastructure behind each node. In other words, the analysis focuses on the interaction of supply and transmission infrastructure across nodes and not within nodes.

Nodal Configuration (UK + Neighbouring Regions)



NUTS 1 UK regions:

- **S**: Scotland
- **E**: East of England
- **NW**: North-West
- **YH**: Yorkshire & Humber
- **EM**: East Midlands
- **WM**: West Midlands
- **W**: Wales
- **E**: East of England
- **L**: London
- **SE**: South-East
- **SW**: South-West

These nodes are used to represent future offshore wind hubs

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1. Subsea interconnections (existing and planned) are not shown but are included in the model setup.
2. London (L) is taken as the Greater London Area allowing, for example, for connections across EM-L and SW-L.
3. IE (Ireland) represents the Republic of Ireland and Northern Ireland.
4. NE (Northern Europe) represents Norway, Sweden and Denmark.
5. WE (Western Europe) represents France, Belgium, the Netherlands and Germany

Modelling Configuration

The LCP model is a capacity expansion and dispatch optimisation model adapted to the characteristics of GB's gas and electricity infrastructure

Temporal Granularity

Our analysis uses six (6) representative days; four (4) seasonal days, a winter peak-day, and a winter supply/demand extreme.

These representative day are used to model the hourly balancing of electricity and gas supply resources and demand profiles of electricity, methane and hydrogen.

Season	Days
Winter	83
Winter Peak	1
Winter Extreme	7
Spring	91
Summer	91
Fall	91
Total	**365**

Regional Granularity

The geographic dimensionality of the analysis covers 11 GB regions, 7 offshore nodes, and 3 neighboring regions. Each region is treated as a "copper plate". The energy system simulated by these 21 regions represents a highly-interconnected electricity and gas system.

Region	Regions	Functionality
GB Onshore Nodes	**x11** (S, NE, NW, YH, NI, W, WM, EM, SW, SE, L, E)	Includes supply and demand of all energy carriers. Supply includes most electricity and gas supply technologies.
GB Offshore Nodes	**x7** (S-OF, NE-OF, YH-OF, E-OF, W-OF, SW-OF)	No demand, only supply. Candidate supply techs are limited to offshore wind and electrolysers. Interconnections options are limited to subsea HVDC and subsea pipelines.
Neighboring Nodes	**x3** (IE = ROI + NI, WE = FR + BE + NL + DE, NE = NO + SE + DK)	Includes supply and demand of electricity, but not methane or hydrogen demand. Supply includes most electricity supply technologies, depending of supply mix of each region.

Energy Carriers

The analysis models energy demand and supply across three carriers: electricity, methane and hydrogen. Links between sectors, such as the use of electricity and/or methane to produce green and blue hydrogen, or to produce electricity with hydrogen or methane are included..

	Cross-Sector Linkages
Electricity	Electricity can be used to produce hydrogen; whether via dedicated generation capacity or the grid. Methane and hydrogen can be used to produce electricity. Electricity can be also be imported or exported across interconnectors to neighboring regions as needed.
Methane	Methane refers to both natural gas and biomethane. Methane can be used to produce blue hydrogen (via SMR+CCS) and electricity (via GT). Methane is imported to GB from Norway, UKCS, Continental Europe and via LNG. Methane can also be exported from GB to IE. Biomethane can be produced domestically in a subset of GB regions – W and SW.
Hydrogen	Hydrogen can be produced domestically (blue via SMR+CCS and green via electrolysis) or it may also be imported from or export to Western Europe or Ireland once gas interconnections are repurposed to hydrogen. Hydrogen can be used to produce electricity.

This section describes a selection of limitations of this study's modeling approach which may have a material impact on results

Modelling of Energy Supply & Demand

For all of GB's 11 NUTS1 regions:

- Electricity, hydrogen and methane demand (2020, 2030, 2040 and 2050) are defined exogenously based on the three FES net-zero scenarios and not optimised as part of the analysis. **Note**: The FES defines energy demand for GB, however, in this analysis, we have disaggregated demand across all NUTS1 regions.
- This means, this study does not model self- and cross-price elasticities across energy carriers. In other words, by adopting pre-defined demand scenarios, our analysis does not model how energy carrier costs may impact their own demand, nor how the cost of one energy carrier may impact demand for another carrier. For example, lower costs for hydrogen vs. biomethane may encourage a shift towards hydrogen use by end-users. These supply-demand dynamics are not captured by our analysis because static, pre-defined demand scenarios are adopted.
- The rationale for adopting pre-defined scenarios of energy demand is to ensure consistency with National Grid's FES scenarios.
- Ultimately, the objective of this analysis is not to identify the best and optimal scenario of energy demand through 2050, but rather to explore the development and operation of electricity and gas transmission infrastructure across a variety of scenarios.

Neighbouring regions:

- Electricity, methane and hydrogen demand in neighboring regions are exogenously defined based on the 2022 TYNDP Global Ambition scenario.
- Our analysis simulates electricity and gas interconnections between any of GB's 11 NUTS1 regions and any of the 3 neighboring regions. We do not, however, model electricity and gas interconnections within these 3 neighboring regions. Rather, we model each individual neighboring region as a "copper plate".
- As with GB, we do not explicitly model supply-demand elasticity dynamics in any of these 3 neighboring regions given that we adopt pre-defined scenarios of 2020-2050 energy demand.

Spatial Dimensionality

- As described previously, this analysis applies a nodal configuration to model an energy system made up of 11 GB nodes, 7 offshore nodes and 3 neighboring nodes. Each region is treated as a single node with supply and demand varying across the study timeframe. **Note:** The only exception is offshore nodes, which are only used to simulate supply and do not capture demand. By extension, this also means our analysis does not capture any sub-regional or spatial (locational) granularity within each of these 21 nodes.
- The lack of further spatial dimensionality means that some technical and operational constraints are not and cannot be explicitly accounted for. For example, the geospatial layout of the electricity or gas distribution system within any of the 11 GB nodes is not explicitly modelled. This may mean technical constraints on electricity, methane and hydrogen supply and transport cannot be explicitly modelled.
- To mitigate the impact of these limitations, Guidehouse and energy entities Grid will work together to capture as much detail as realistically possible via alternative modelling levers and methods; for example, by imposing constraints and limitations on technically-unfeasible or technically-unlikely outcomes, in order to avoid unrealistic and questionable results.

Impact of Policy on Energy Infrastructure

- While this study aims to adequately simulate the operation and evolution of GB's electricity and gas systems - a system made up of GB's 11 NUTS1 regions and three (3) neighboring regions (Ireland, Western Europe and Northern Europe) – the results of this analysis are not intended to dictate when and where supply and transmission infrastructure investments may take place.
- The results of our analysis will be purely reflective of a cost-optimisation modelling exercise and may not reflect the complexities and intricacies of interjurisdictional policy-making, security of supply and system/resource adequacy requirements, or other regulatory, technical and operational constraints. Findings from this study should be read in this context and should take into consideration limitations of the analysis.

Seasonal Representative Days

- Our analysis is configured to use an intra-annual temporal resolution based on six (6) representative 24-hour days. Four (4) of these representative days are seasonal days (e.g., winter, spring, summer and fall), the 5th day is a winter-peak day, and the 6th is a supply-demand extreme (intended to reflect a dunkelflaute).
- These representative days are used in lieu of modelling a complete 8760-hourly profile for a full year in order to achieve a balance of computational demand (and model runtime) with modelling accuracy.
- Each of these representative days capture hourly demand and supply profiles. Supply profiles for intermittent resources like wind, solar and hydro reflect real, hourly inter-daily variations and intermittency in their production profiles.
- The selection of intermittent production profiles can have a significant impact on results. For example, a poorly chosen wind profile can overestimate or underestimate wind production throughout the year. Similarly, a day with particularly drastic hour-to-hour variations in wind output can also yield skewed results.
- Guidehouse applies a rigorous analytical exercise for the selection of the intermittent production profiles underlying this study.

Electricity Development

This section presents detailed **electricity system results** from two different **whole system scenarios**:

System Transformation and **Consumer Transformation**

What is covered:

- Electricity Demand
- Electricity Supply
- Electricity Infrastructure

Leading the Way was also modeled as part of this study, however results are not shown as ST and CT results present the two extremes

Electricity key takeaways

The modeling shows that the increasing regional supply-demand imbalances will require increased GB-wide coordinated approach to transmission network development to minimise system costs, over and above that is currently undertaken.

A geographically coordinated approach to transmission network development is needed to optimise and accommodate the transport of the unprecedented increase in electricity supply capacity in some regions such as Scotland with more than 100 GW of renewables installed capacity by 2050.

Curtailment could be greatly reduced in an integrated scenario with the introduction of electrolysis and storage with renewable generation, unlocking their full potential by providing optionality to the power produced.

In a limited integration scenario, introducing electrolysis, as well as other technologies into the energy mix has the potential to greatly reduce renewable generation curtailment. This can lead to reduced energy costs and greater investment incentives with more stable revenues for developers.

Harnessing the opportunities of weather-dependent renewable energy sources requires you to increase the role of demand side flexibility and dispatchable peak generation

The scale-up of weather-dependent renewable resources increases the importance of supply-side flexibility and demand-side flexibility resources.

Early strategic investments in electricity transmission infrastructure are needed today to accommodate for the increase in renewable generation and reduce it cost

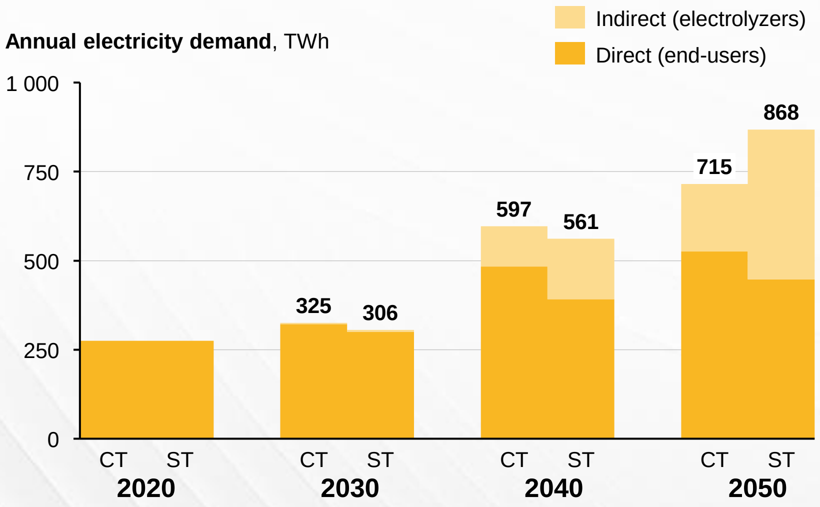
Strategic, whole system investments in new transmission infrastructure will be needed in across the modeled project scenarios to support the development of renewables and meet demand across the country. Taking investment decisions promptly will allow for better network integration which will result in reduced power generation costs and attract investments to build the required supply capacity. This need resonates with other studies conducted in the past year, such as the Offshore Transmission Network Review, Network Planning Review and others.

ST **CT**

Electricity demand increases significantly from 2020 to 2050 across both scenarios

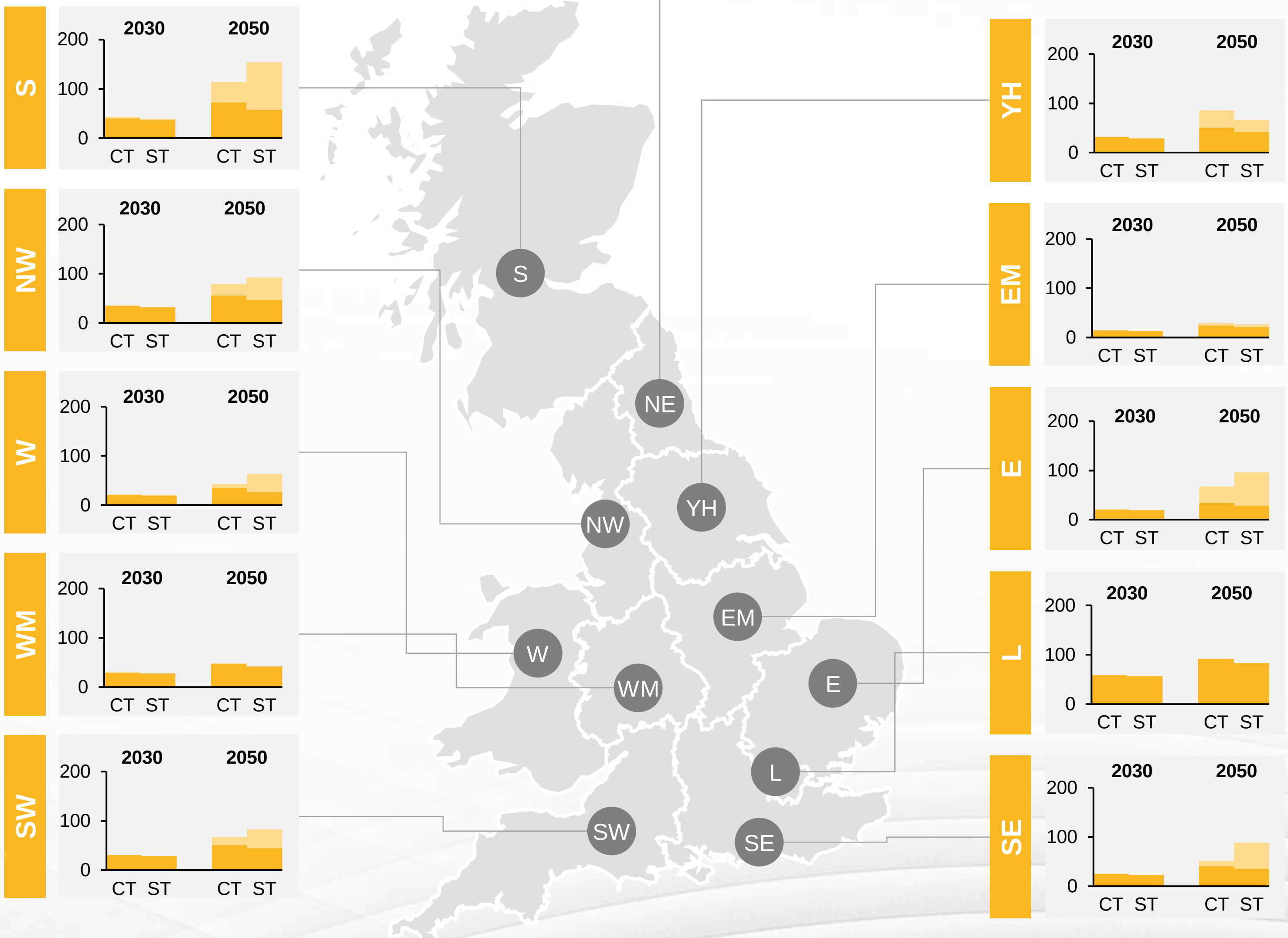
Key Messages

- **Electricity demand increases significantly from 2020 to 2050** across both scenarios.
- **Electricity demand is higher in ST than CT in 2050** due to significant demand used for **green hydrogen production.**
- **Demand increases the most in Scotland and the East of England**, where green hydrogen production is significant.



Annual electricity demand, TWh

Annual Electricity Demand, TWh

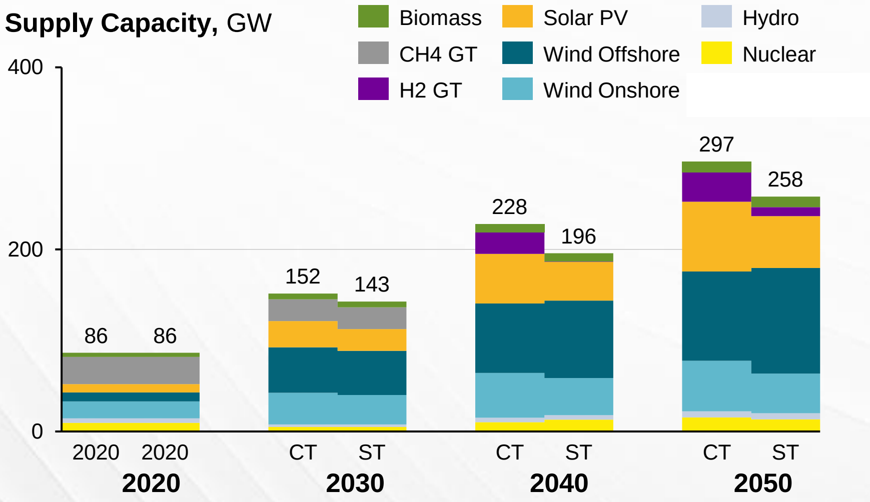


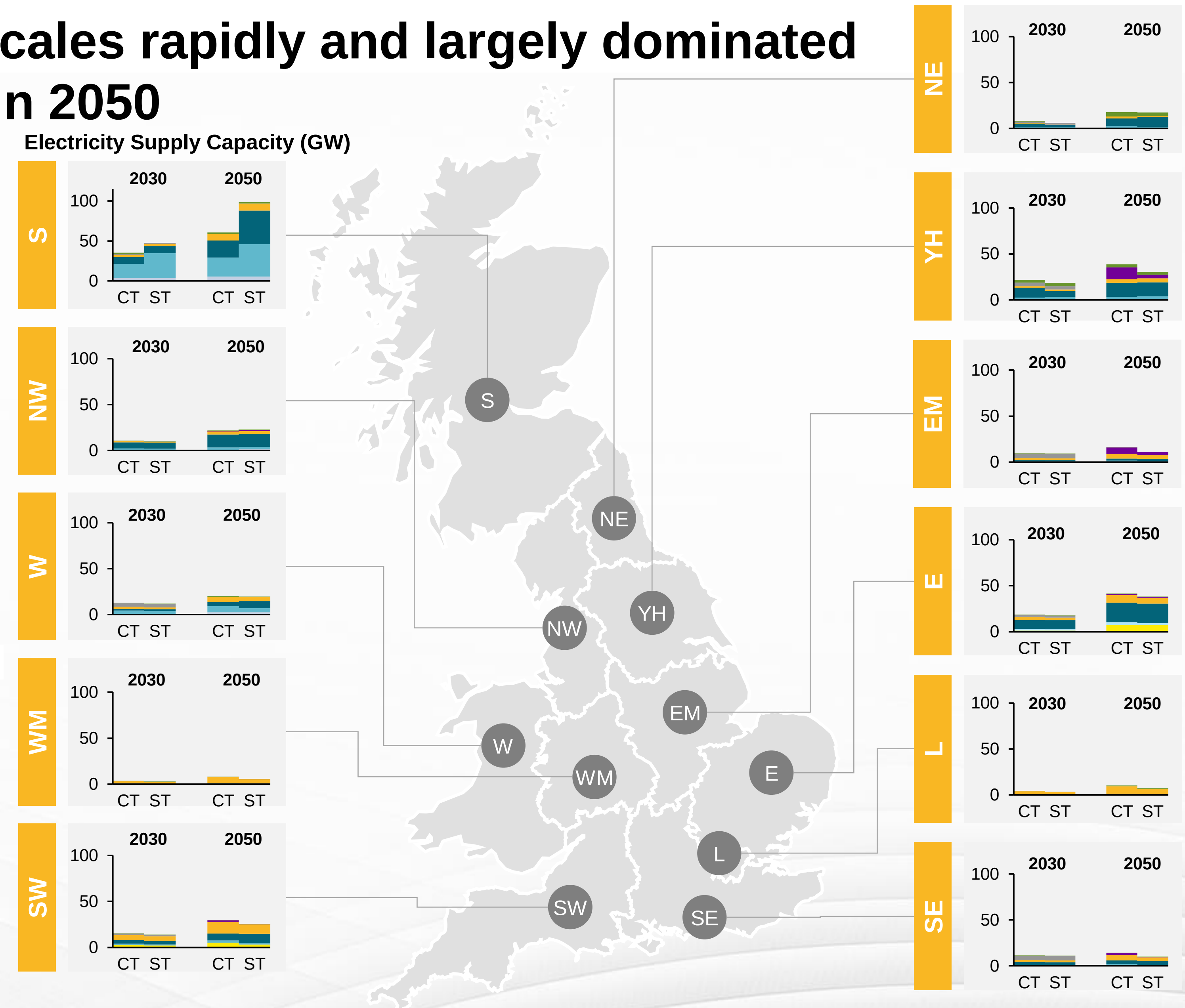
ST **CT**

Electricity supply capacity scales rapidly and largely dominated by wind and solar resource in 2050

Key Messages

- **Offshore and onshore wind capacity scales up significantly** in both scenarios.
- **Scotland** and the **East of England** become **major supply regions**, largely driven by increased offshore and onshore wind capacity.
- By 2050, **nearly 90% of generation capacity is from intermittent resources** vs 50% today.


Supply Capacity, GW

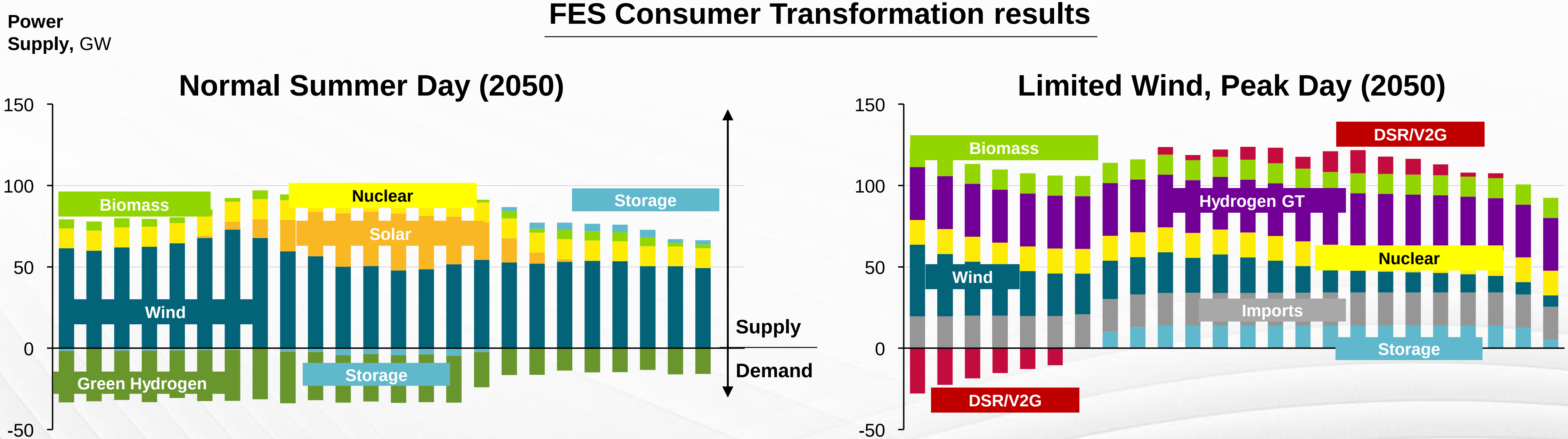

Electricity Supply Capacity (GW)

Flexibility resources become increasingly important as the energy system transitions to renewables towards 2050

Key Messages

- **Renewable generation is key to meeting UK net-zero ambition.** This increases the importance of dispatchable peak supply as demand is met largely with renewables on normal days; whereas on limited-wind days, renewables only play a very limited role.
- **Reliance on renewables increases the importance of flexibility options** both in terms of demand and supply.
- **Hydrogen turbines** play key supply role, offering reliable domestic supply alternatives. In a highly electrified scenario, more than 32GW of hydrogen turbines are needed to meet demand.

FES Consumer Transformation results

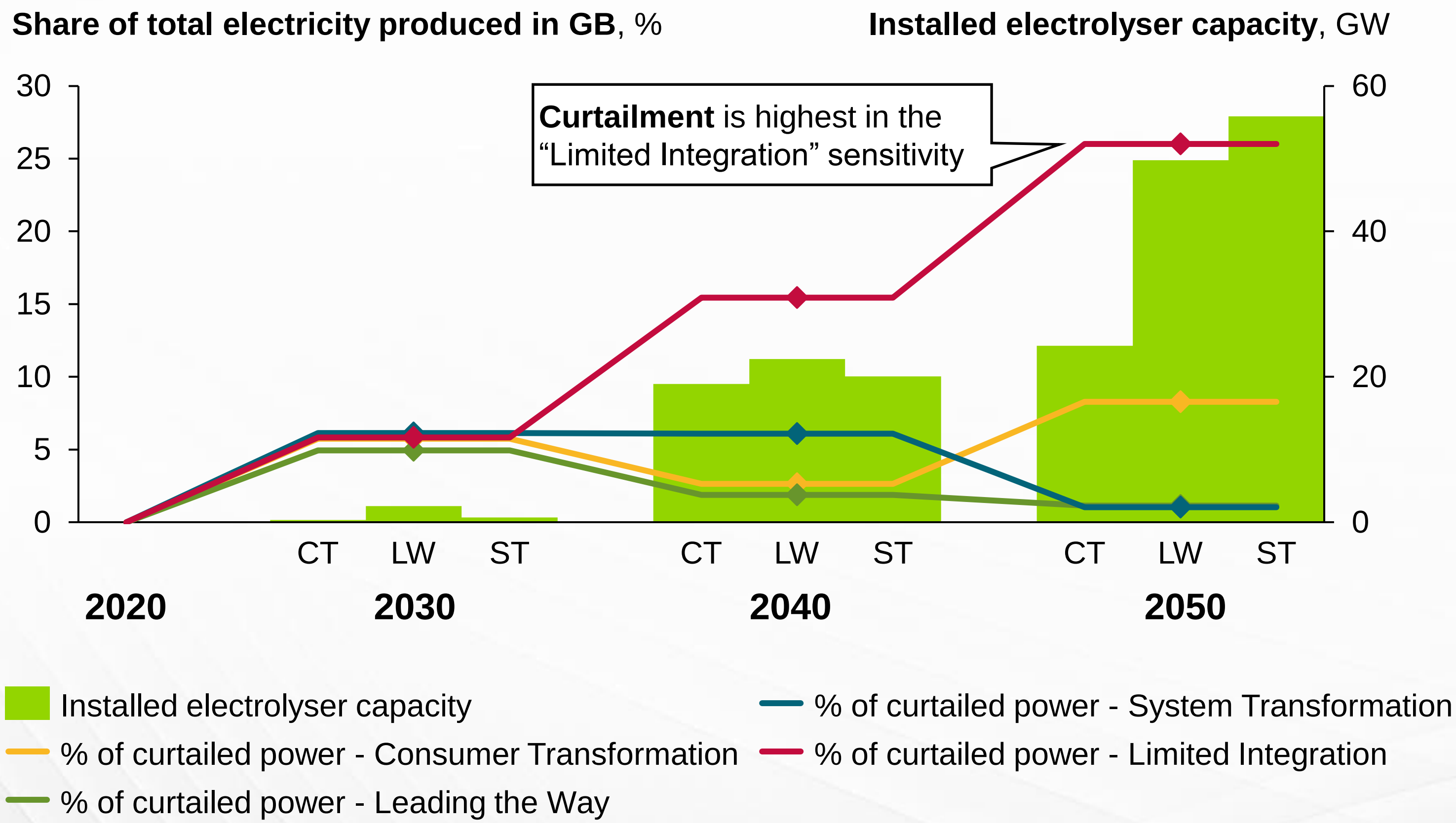


Note:
1. Graphs only show power supply resources (e.g., nuclear, wind, solar storage, etc.) and not end-user demand (e.g., buildings, industry, etc.)
2. Nuclear, biomass and imports are capped as per FES assumptions to reflect political and supply chain constraints

ST **CT** **LW** **FES scenarios**

Curtailment is minimised in all integrated scenarios, and is highest in the Limited Integration sensitivity

Electrolyser capacity has an impact on share of curtailed power



Key Messages

- **Curtailment reaches over 26% of annual supply in a limited integration world** compared to less than 1% in the integrated ones.
- In 2050, LW and ST have at least two times higher installed electrolyser capacity than CT; **this leads to 8 times less curtailment in ST and LW.**
- **In 2040**, despite having about the same electrolyser capacity in ST as CT, **the share of electricity curtailed is higher in ST** due to the role of other solutions.
- **Other solutions,** such as interconnectors, storage and demand side flexibility, **play a role in limiting curtailment.**

Note: *The analysis does not consider curtailment due to transmission & distribution network constraints.*

Note: Refer to detailed methodology slides for more information on the modeling approach.

ST **CT**

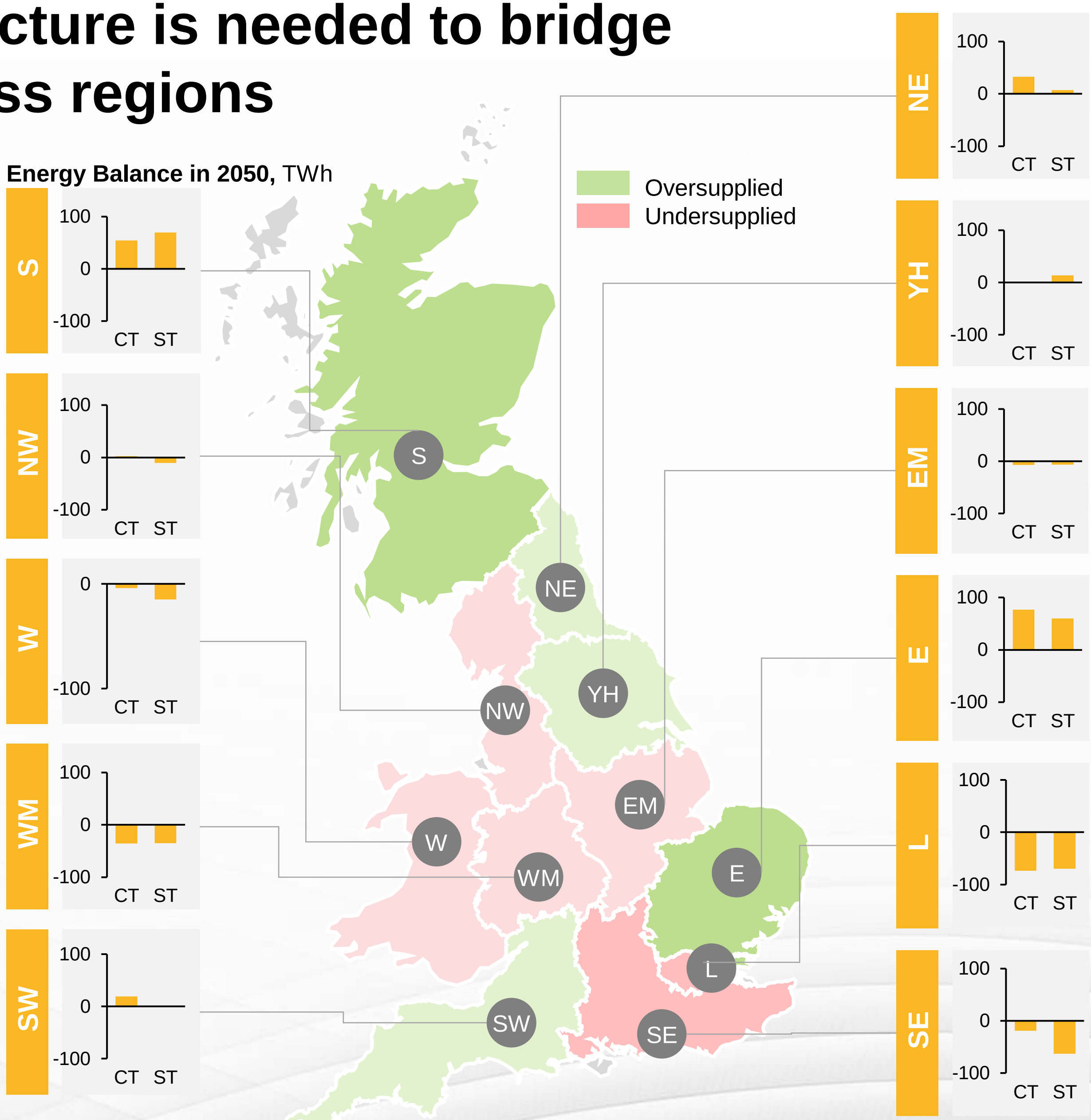
Electricity transmission infrastructure is needed to bridge supply-demand imbalances across regions

Key Messages

- In both scenarios, there are **significant differences in the electricity supply-demand balance** across regions.
  - Some regions – like **Scotland, the East of England and the North-East** – are characterised by a **net oversupply of electricity,** benefitting from abundant renewable potential.
  - Other regions – like **London, the South-East and the West Midlands** – require **electricity supply from neighboring regions** to meet demand.
- The expansion of existing and development of new **electricity transmission infrastructure are needed to bridge these differences**.
  - For example, new transmission infrastructure will be needed to support onshore / offshore wind development in Scotland and the East of England.

***Note:** In CT, GB becomes net exporter in 2050 while it is a net importer in ST*

Energy Balance in 2050, TWh

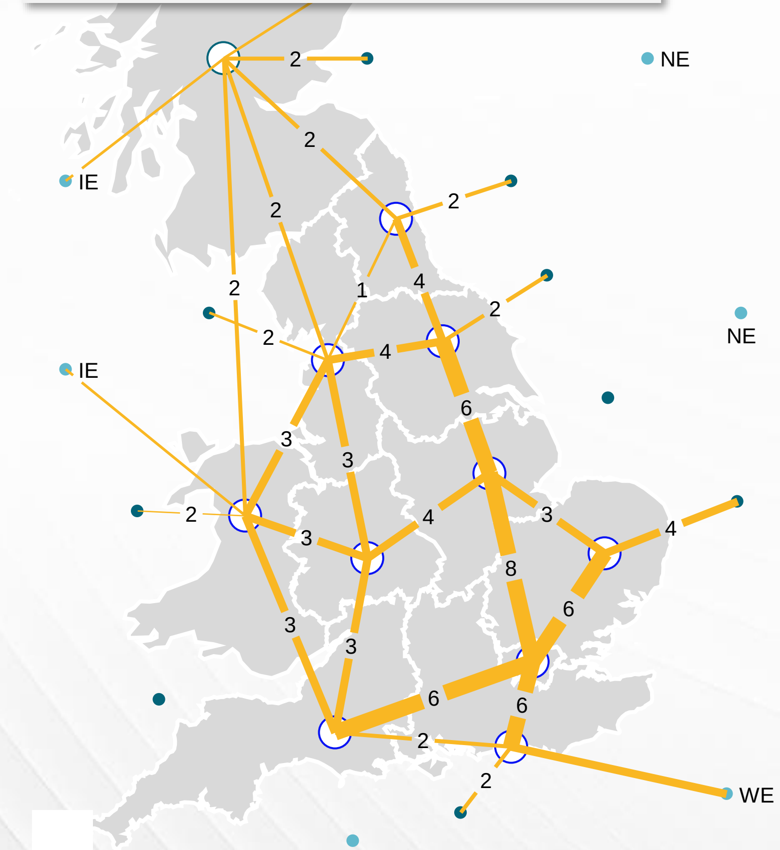


ST CT

Electricity transmission infrastructure increases significantly, particularly in the North and offshore regions, where renewable energy potential is vast

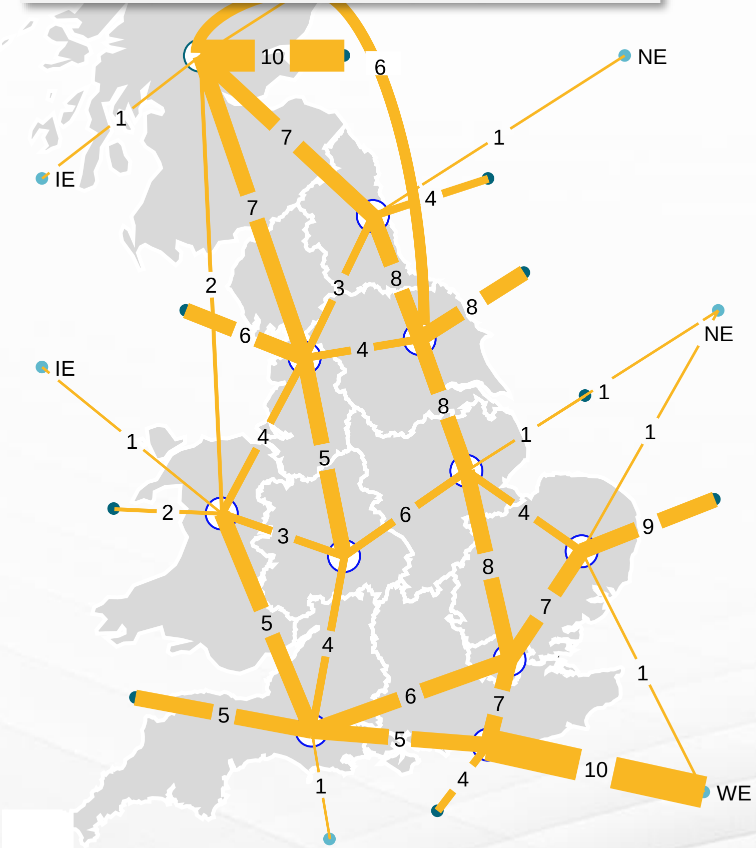
2020

Existing transmission network is **highly interconnected across GB** and includes some offshore interconnections.



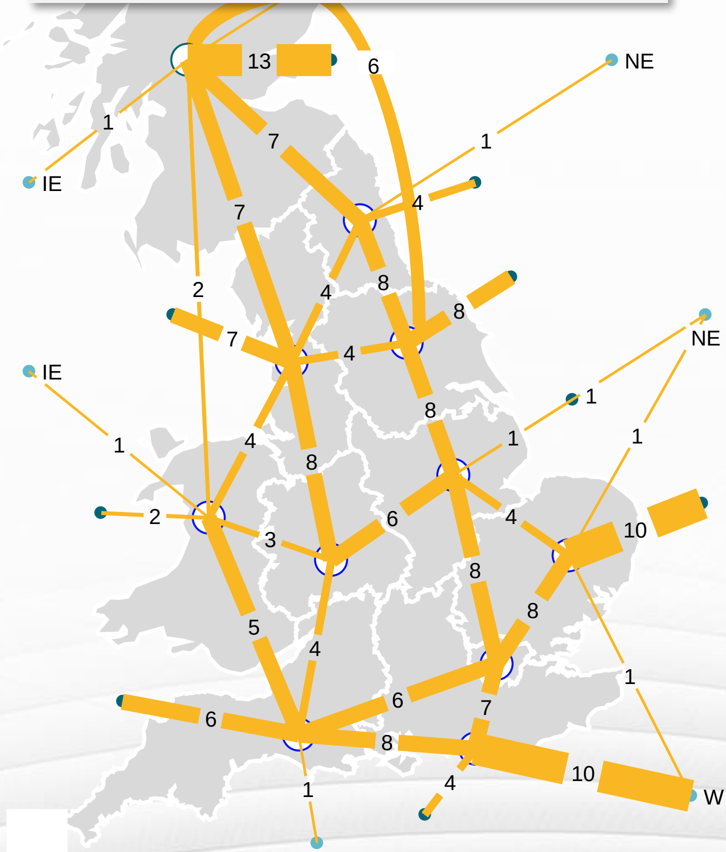
2040

Large buildout of interconnection capacity across GB, accommodating the scale-up in new supply capacity



2050

Reinforcement of electricity transmission infrastructure across the country**.**



Guidehouse Outwit *Complexity*

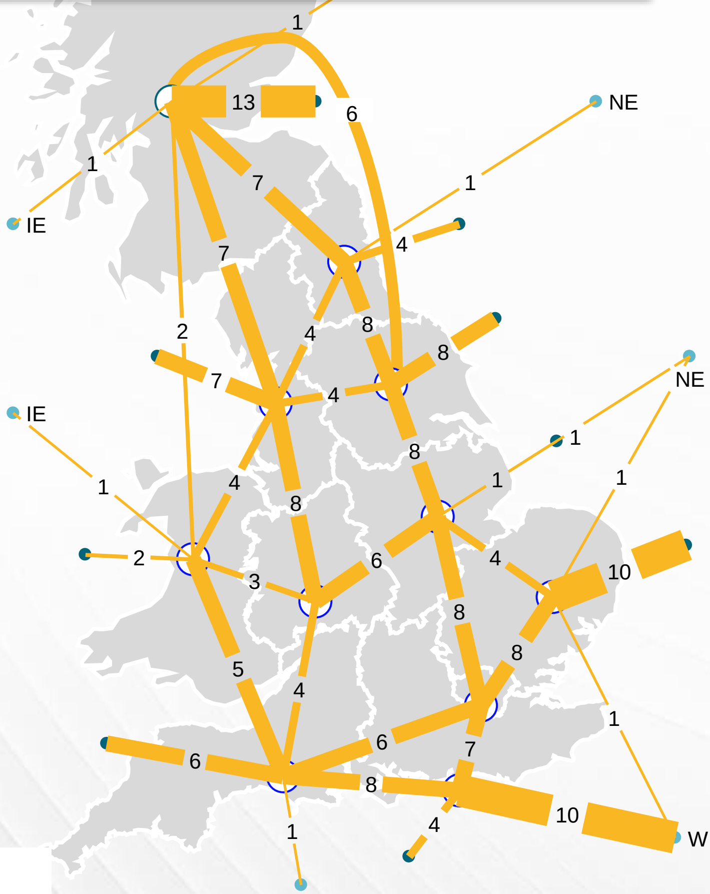
Note: (1) These maps present a simplified representation of GB's electricity transmission network defined by the nodal configuration used in this study and do not accurately reflect the real-world configuration of the network. (2) Transmission capacities reported in the maps represent minimum operational capacity needs, and not rated nameplate capacities. (3) Analysis results may not incorporate the latest planned or approved transmission and supply investments, nor recently-defined targets. (4) Holistic Network Design has not been considered; thus, capacity expansion may be different.

ST **CT**

Similarities in electricity transmission network development across scenarios highlight the need for expansion in all visions of the future

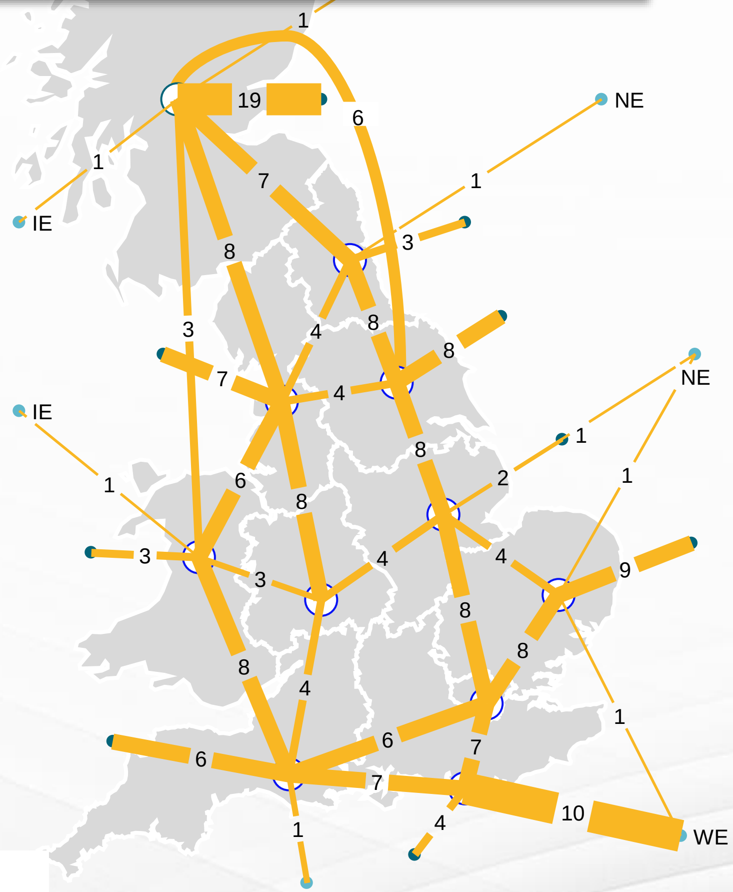
2050 - CT

Buildout of transmission network supports **doubling direct demand** by 2050 in CT.



2050 - ST

In ST, in a hydrogen-focused scenario, **2050 grid development is similar to CT.**



Key Messages

- In both CT and ST, **significant reinforcement** of the electricity transmission infrastructure is needed across the country.
- **Similarities in the electricity transmission network** across the two scenarios highlight common, no-regret investments in reinforcing and expanding transmission infrastructure along North-South and East-West corridors.
- As with any study, **there is inherent uncertainty around the development, scale and detailed design** of the electricity transmission network. Further analysis could be conducted to determine this post 2030.

Note: (1) These maps presents a simplified representation of GB's electricity transmission network defined by the nodal configuration used in this study and does not accurately reflect the real-world configuration of the network. (2) Transmission capacities reported in the map represent minimum operational capacity needs, and not rated nameplate capacities. (3) Analysis results may not incorporate the latest planned or approved transmission and supply investments, nor recently-defined targets.

Hydrogen Development

This section presents detailed **hydrogen system results** from two different **whole system scenarios**:

System Transformation and **Consumer Transformation**

What is covered:

- Hydrogen Demand
- Hydrogen Supply
- Hydrogen Infrastructure

Leading the Way was also modeled as part of this study, however results are not shown as ST and CT results present the two extremes

Hydrogen key takeaways

From the project modeling the hydrogen imbalance shows a need for a GB-wide hydrogen network, the scale and design of which differs with each scenario.

The scale and design of the backbone differs depending on purpose and need for hydrogen. In a high hydrogen demand scenario, the backbone delivers low-cost hydrogen from regions with excess supply to regions with high demand. However, in a high electrification scenario, the backbone plays a key role in delivering hydrogen to H_2 Gas Turbines across the country

In a high hydrogen demand scenario, a GB-wide backbone delivers low-cost hydrogen from regions with excess supply to regions with high demand. In a high electrification scenario, the network is more limited playing a key role in delivering hydrogen to H2 Gas Turbines across the country

In System Transformation, a scenario with significant hydrogen demand, blue hydrogen plays a key role in 2030 and 2040 to meet a rapidly increasing demand. In 2050, while green hydrogen plays a dominant role, delivering low-cost supply and reducing electricity curtailment, blue hydrogen is still needed to provide weather-independent supply to meet the scenario's important residential heating demand.

In all modelled scenarios, hydrogen storage is critical in supporting whole energy system demand during peak demand periods and low wind days

Hydrogen storage plays a critical role during high demand, low wind days, delivering up to 95 GW of firm, dispatchable supply and supporting both the gas and electricity systems. If Great Britain were to keep current gas storage volumes of 10TWh, hydrogen reserve would not last more than 5 days.

Strategically located investments in hydrogen transmission infrastructure are needed in the next decade to deliver the benefits of integrated system planning

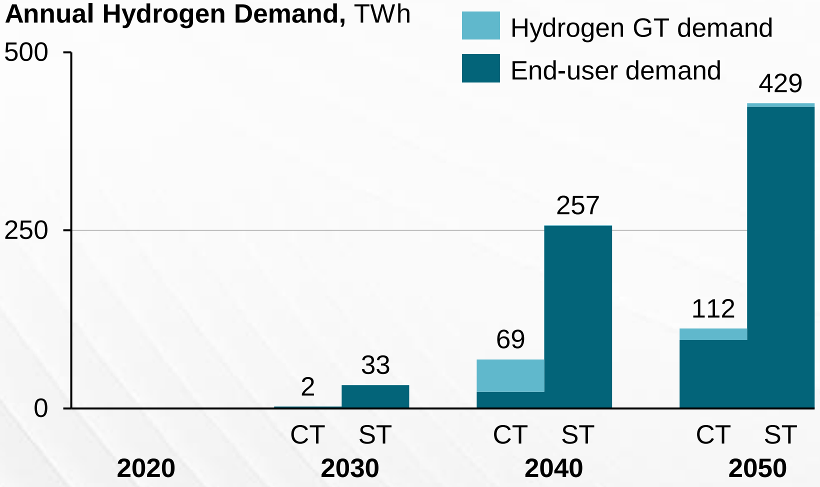
Strategic, whole system investments in hydrogen transmission infrastructure are needed to support the development of renewable generation and meet demand across the country. Taking investment decisions promptly will allow for better network integration which will result in optimised energy generation and attract investments to build the required supply capacity.

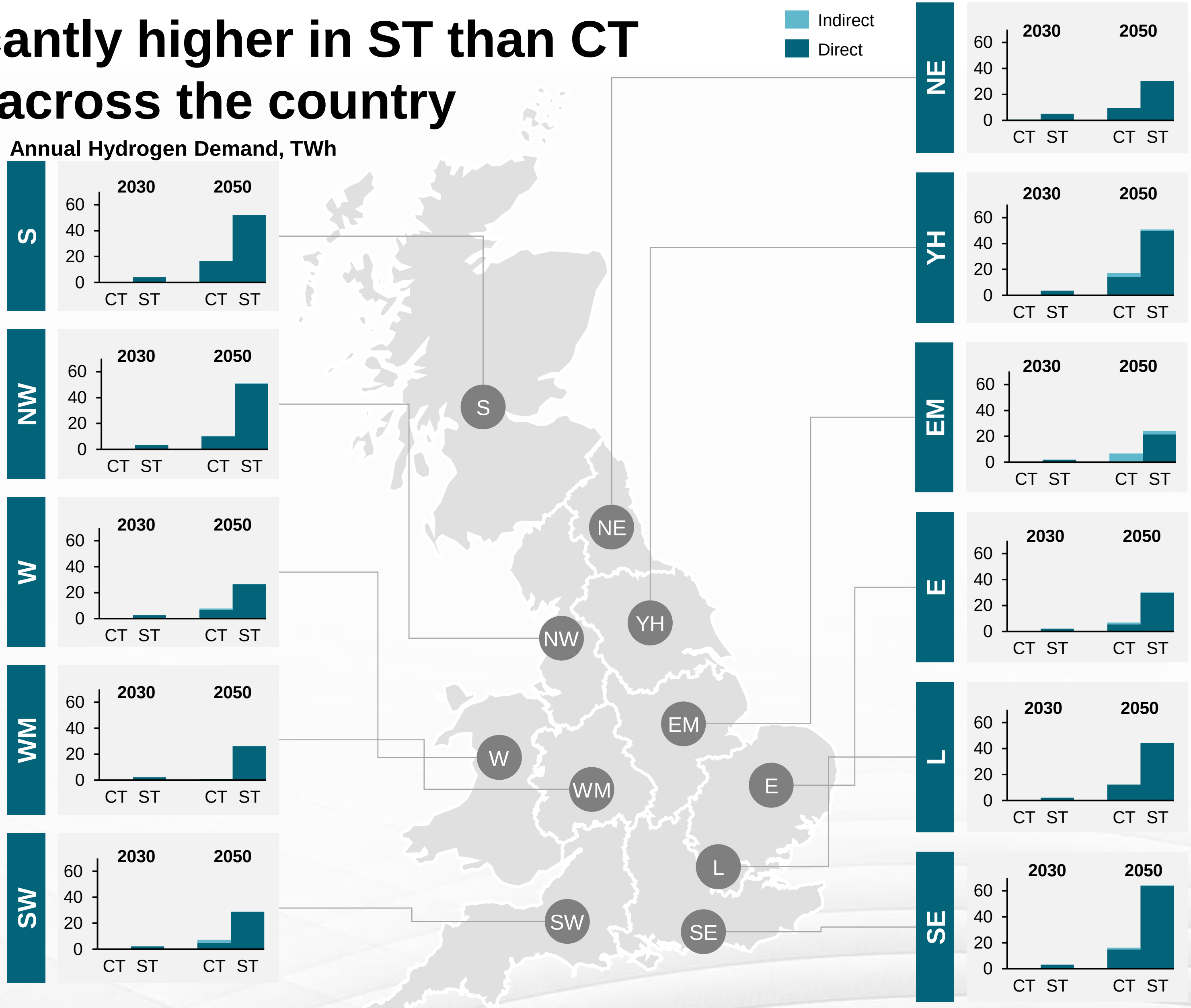
ST **CT**

Hydrogen demand is significantly higher in ST than CT and is unequally distributed across the country

Key Messages

- **Hydrogen demand is significantly higher in ST than CT** largely due to a more significant role of hydrogen in residential heating and industry.
- **Hydrogen demand is highest in Southeast** due to the presence of industrial clusters, large ports and an important building stock.
- Most hydrogen demand by 2030 is related to **industry hubs and blending**.





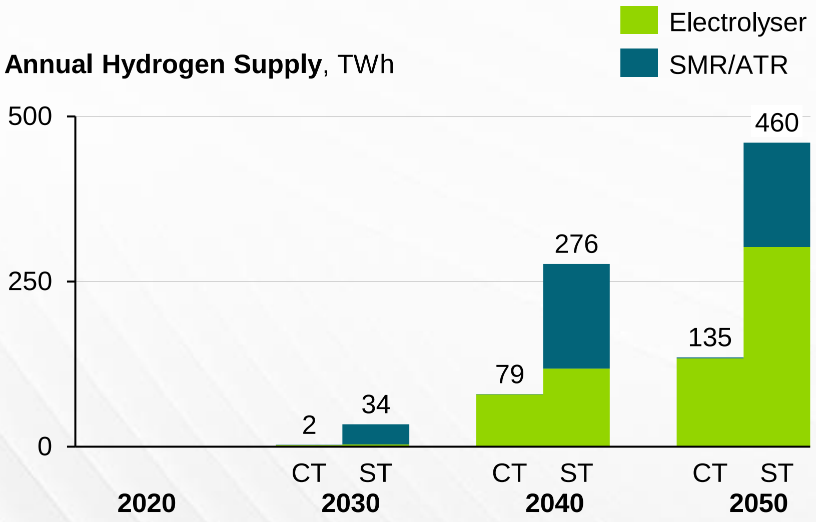
ST **CT**

Blue H_2 plays a key role in the near term and in delivering firm supply, while green H_2 plays a more dominant role by 2050

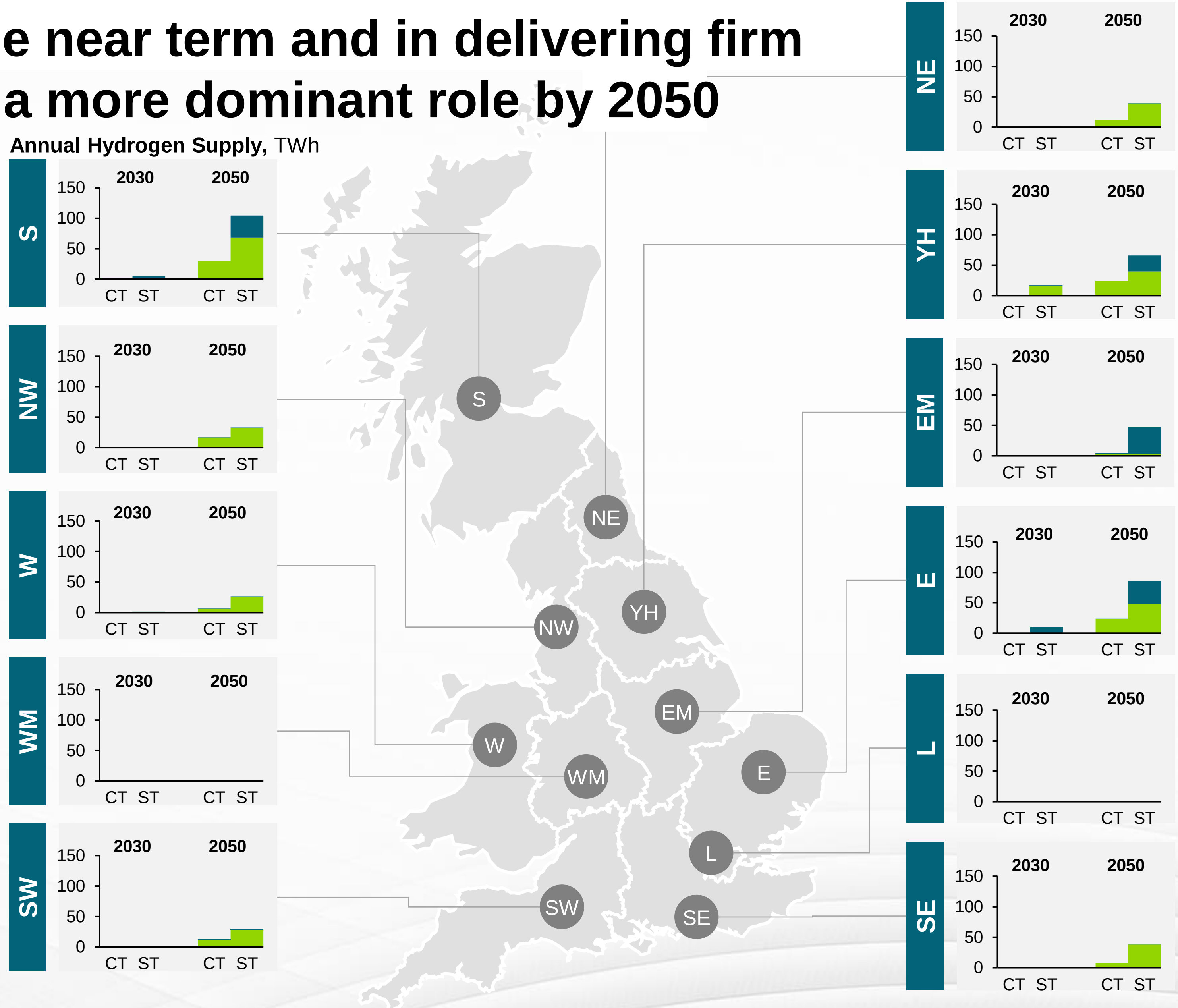
Key Messages

- **In ST, blue hydrogen also scales** rapidly until 2040, but beyond 2040 all new capacity is for **green hydrogen.**
- **In CT,** blue hydrogen plays a limited role as **hydrogen demand remains low.**
- **Scotland, the East and Yorkshire & Humber** become key **hydrogen supply hubs** for GB.

Annual Hydrogen Supply, TWh



Annual Hydrogen Supply, TWh

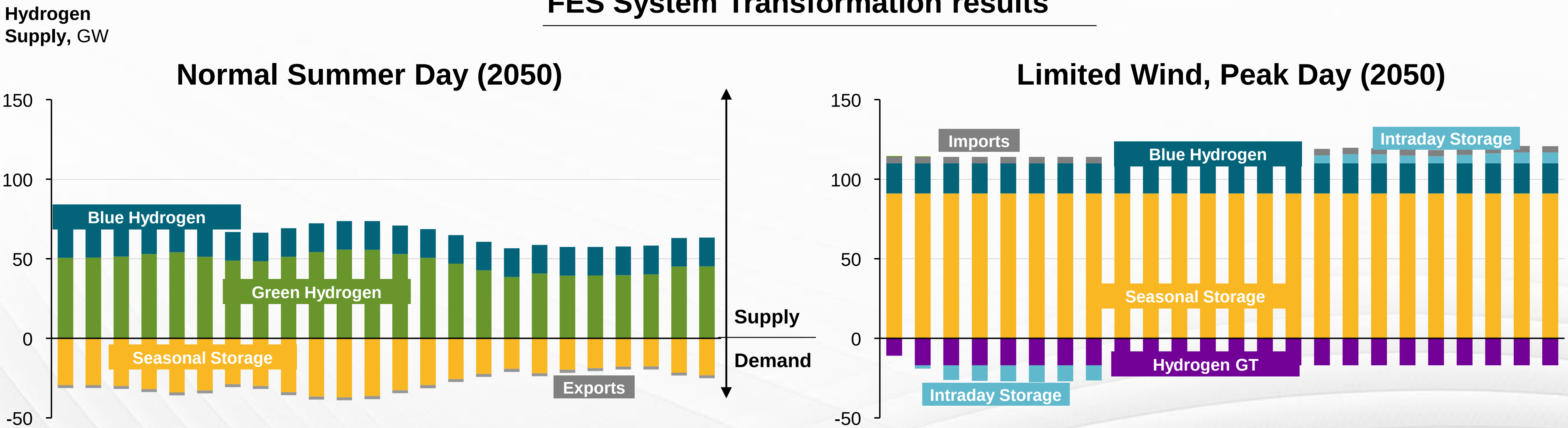


Hydrogen storage plays a key role in maximising the opportunity that green hydrogen provides

Key Messages

- **Hydrogen supply becomes significantly dependent on renewables**, much like electricity supply. On normal days, demand is met largely with green hydrogen; whereas on limited wind days, green hydrogen only plays a very limited role.
- **Reliance on renewables for green hydrogen increases the importance of non-weather dependent hydrogen supply.**
- **Hydrogen storage plays a critical role in meeting hydrogen and electricity demand** on days with very low wind. Robust business models and a clear hydrogen seasonal price spread will be key in ensuring storage is available for use in the winter.

FES System Transformation results



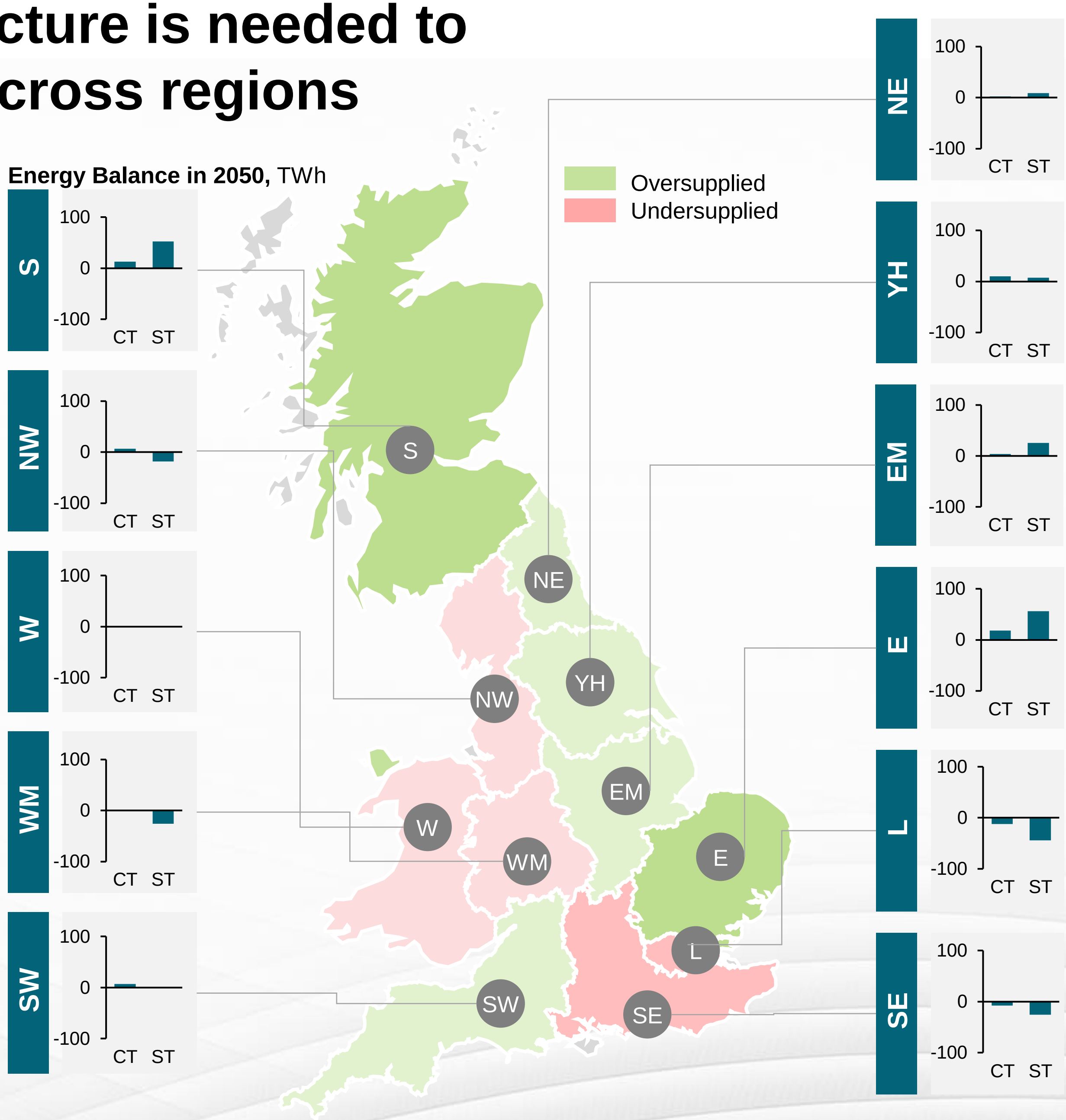
Note:
1. Graphs only show hydrogen supply resources (e.g., green and blue hydrogen, storage, etc.) and not end-user demand (e.g., buildings, industry, etc.).

ST **CT**

Hydrogen transmission infrastructure is needed to bridge supply-demand balance across regions

Key Messages

- In both scenarios, there are **significant differences in the hydrogen supply-demand balance** across regions.
  - Some regions – like **Scotland, the East of England and the East Midlands** – are characterised by a **net oversupply of hydrogen,** benefitting from abundant renewable potential.
  - Other regions – like the **South-East, London and the West Midlands** – require **hydrogen supply from neighboring regions** to meet demand.
- Whilst the design and scale will differ between scenarios, the **repurposing of existing transmission infrastructure** as well as the **development of new infrastructure is needed to bridge these differences.**
  - For example, hydrogen transmission infrastructure will be needed to connect **excess supply from the East of England to demand in London and the South-East.**



Energy Balance in 2050, TWh

Guidehouse Outwit Complexity

ST CT

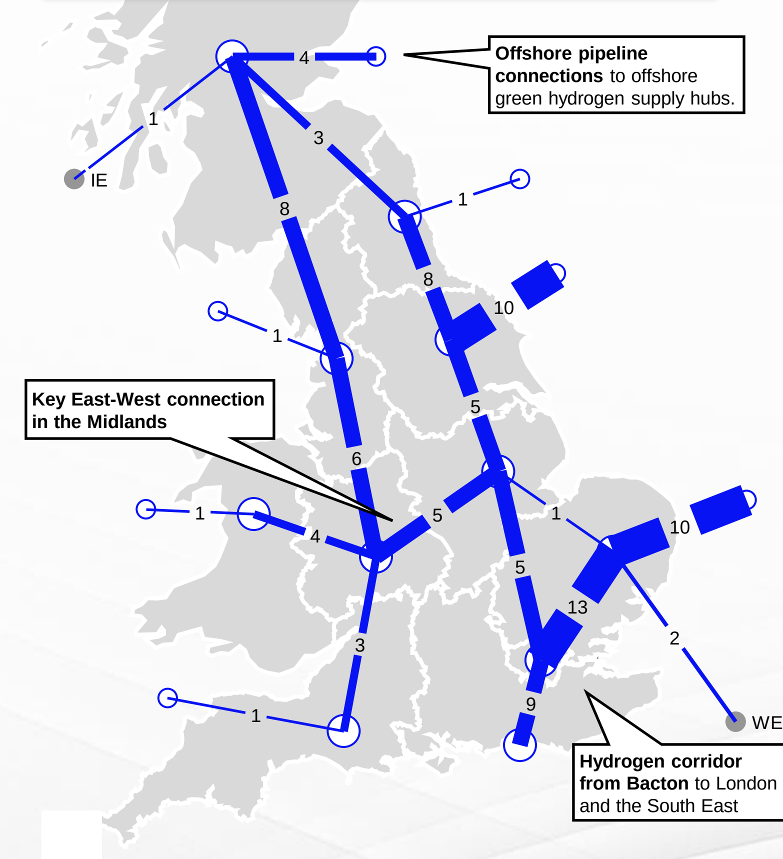
A hydrogen backbone emerges between 2030 and 2040 and is fully developed by 2050

2030 - ST

Early development of a backbone from the Northeast to the Midlands, and between the London and the East of England.

2040 - ST

Transmission backbone emerges across most of GB linking supply hubs and demand regions.



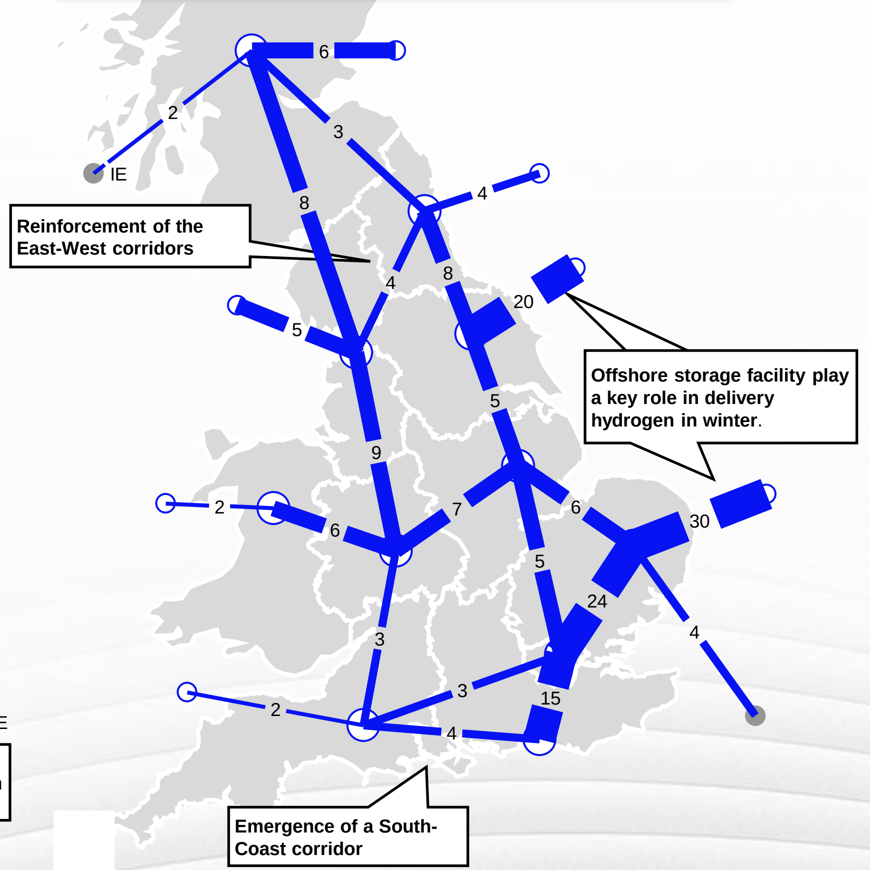
Offshore pipeline connections to offshore green hydrogen supply hubs.

Key East-West connection in the Midlands

Hydrogen corridor from Bacton to London and the South East

2050 - ST

Full development of backbone, and in particular an East-to-South-East connection to meet increasing demand



Reinforcement of the East-West corridors

Offshore storage facility play a key role in delivery hydrogen in winter.

Emergence of a South-Coast corridor

Guidehouse Outwit *Complexity*

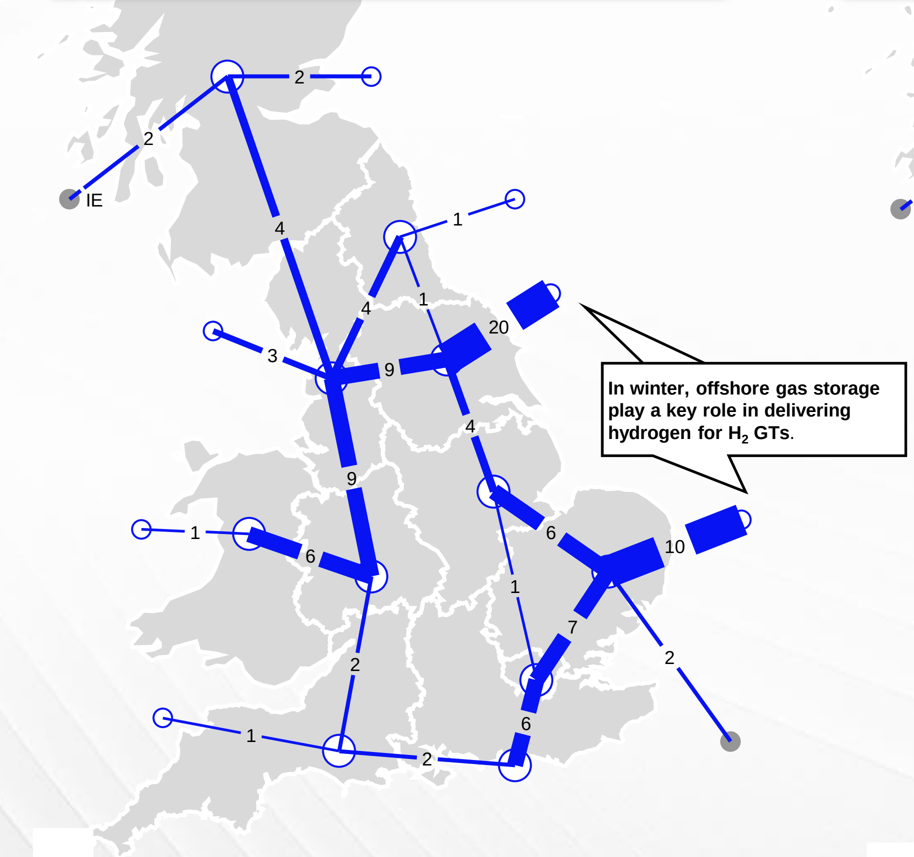
Note: (1) These maps presents a simplified representation of GB's future hydrogen transmission network defined by the nodal configuration used in this study and does not accurately reflect the real-world configuration of the existing natural gas network. (2) Transmission capacities reported in the map represent minimum operational capacity needs, and not rated nameplate capacities. (3) Analysis results may not align with planned hydrogen transmission investments, nor targets.

ST **CT**

In both ST and CT scenarios, a hydrogen network develops by 2050; however, serving different purposes

2050 – CT

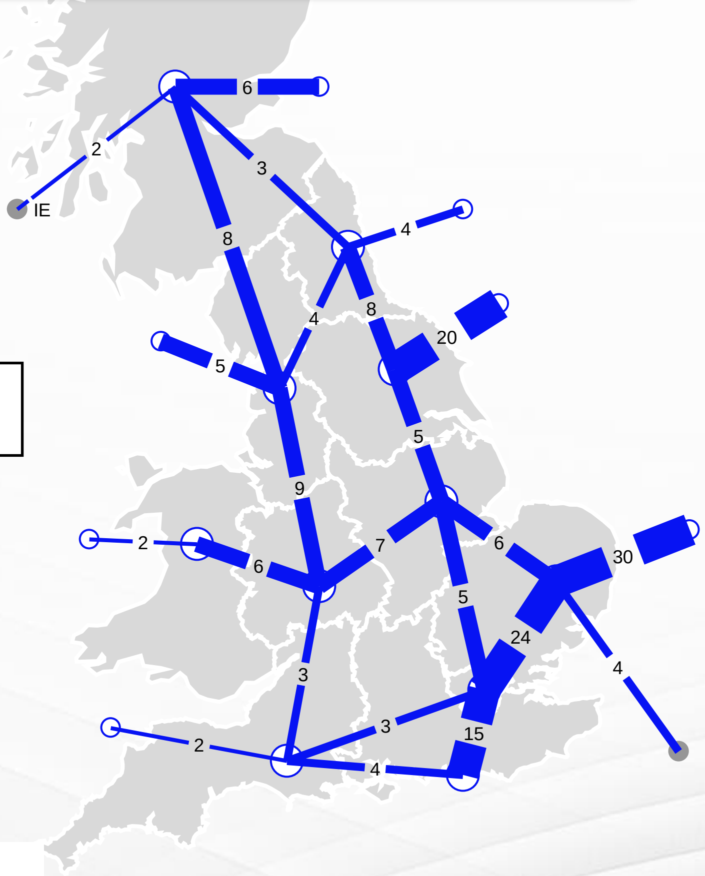
A hydrogen network primarily **delivers hydrogen to H_2 GTs for electricity supply**



In winter, offshore gas storage play a key role in delivering hydrogen for H_2 GTs.

2050 - ST

Hydrogen backbone **connects hydrogen supply and demand.**



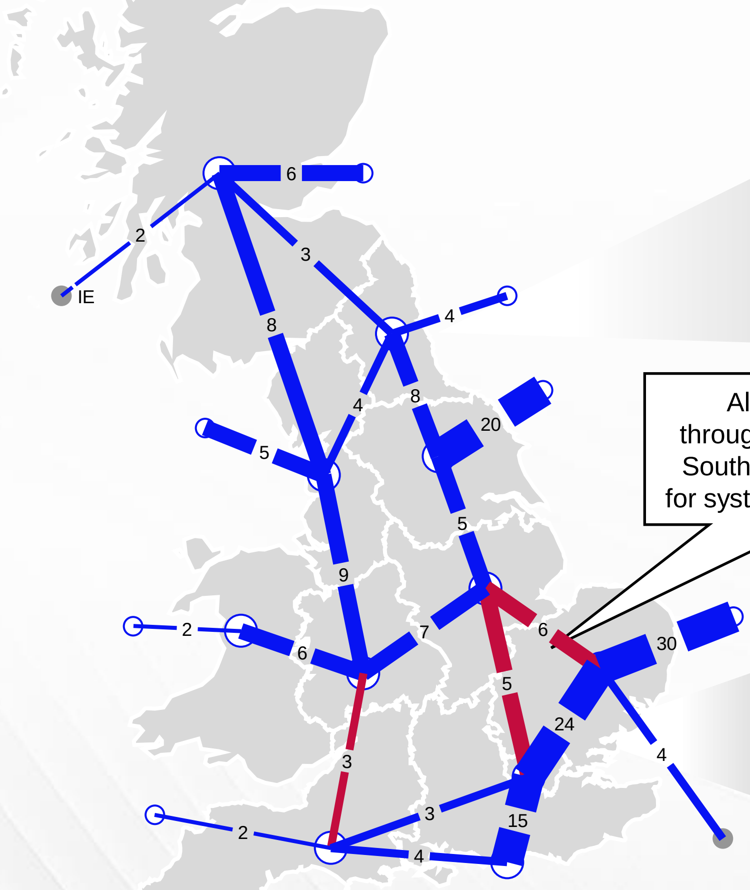
Key Messages

- **Both scenarios show a need for a GB-wide hydrogen network in 2050.** The scale and design of that, however, differs depending on purpose and need for hydrogen.
- **In Consumer Transformation (CT)**, despite limited demand from end-users, a network still develops. This transmission network plays a **key role in delivering hydrogen to H_2 GTs across the country**, roughly 32 GW.
- **In System Transformation (ST)**, the backbone **delivers low-cost hydrogen from regions with excess supply** (Scotland, East of England) **to regions with high demand** (London, South-East).

Note: (1) These maps presents a simplified representation of GB's future hydrogen transmission network defined by the nodal configuration used in this study and does not accurately reflect the real-world configuration of the existing natural gas network. (2) Transmission capacities reported in the map represent minimum operational capacity needs, and not rated nameplate capacities. (3) Analysis results may not align with planned hydrogen transmission investments, nor targets.

The North-South connection sees limited flows throughout the year but is critical in winter, which is important in terms of energy security

2050 - ST

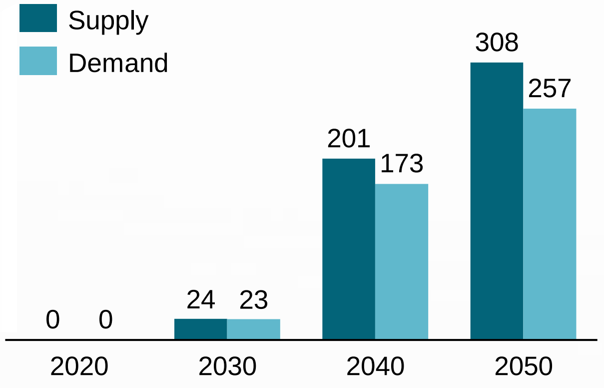


Although less used throughout the year, North-South connection is critical for system resiliency in winter

🟥 Critical for system resiliency

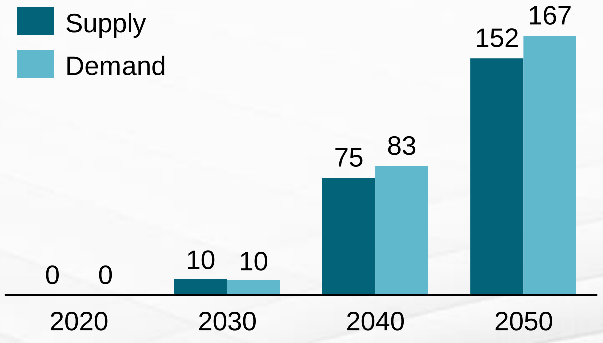
North-Central Region

(Scotland, North England, Midlands and Wales)



South-Coast Region

(East, South-East, South-West and London)



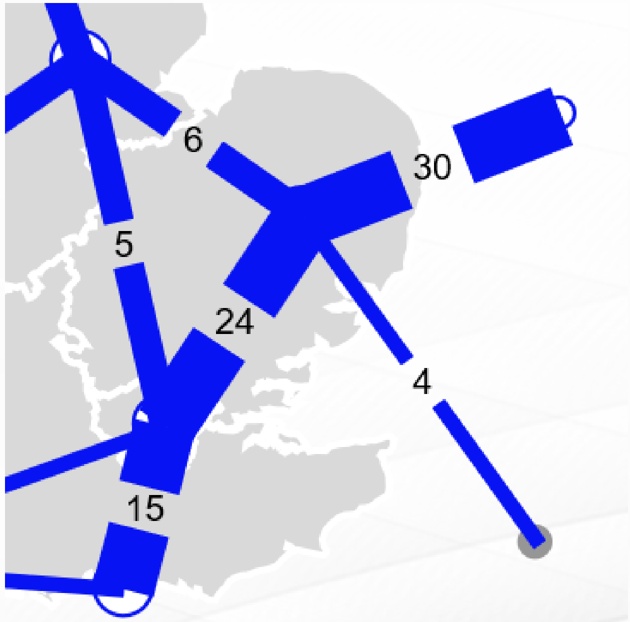
Key Messages

- Our analysis shows **limited need for connection between the North and South of England**
- However, **these North-South corridors play a critical role during the winter and during peak periods** in delivering hydrogen to end-users, to H_2 GTs (for electricity supply), as well as to and from storage facilities
- These N-S hydrogen corridors emphasise the **importance of diversity of supply and ensure network resilience**

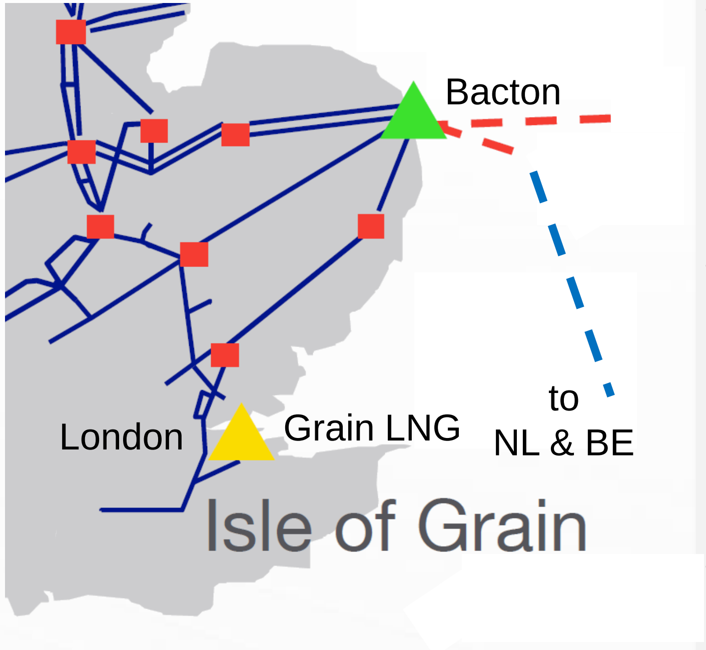
ST CT

The cost optimal output is to deliver supply from Bacton to the South-East direct, however, energy security needs to be factored in

2050 - ST



2020 network route map



Key Messages

- The modelled cost-optimal infrastructure sees **24 GW of hydrogen pipeline assets delivering hydrogen from Bacton to London**, whereas the share of hydrogen pipeline capacity from Bacton into central England is limited to 5GW
- **In reality the regional pipeline infrastructure needs to be designed akin to today's arrangement** where natural gas from Bacton is apportioned between direct routing to London, and Central England, where gas is disseminated between London and other regions
- **The current setup delivers security of supply and resilience** benefits to the critical London demand center, which the model doesn't account for
- **Further work** could address the regional disparities in infrastructure created from a cost optimal view

Sensitivity Scenarios

What is covered

- #1 – Hydrogen Exporter
- #2 – Limited gas storage
- #3 & #4 – All scenarios energy infrastructure comparison
- #5 – Limited Integration World

#1 - Great Britain can unlock the benefit of being a hydrogen exporter provided that the hydrogen network infrastructure is there to support it

Key Results

- In **Hydrogen Exporter**:
  - **Offshore wind, SMR** and **electrolyser** capacity scales up to meet increased exports.
    - As offshore wind scales up, the location of **electrolysers shifts closer to supply** from onshore to offshore sites, minimising the buildout of electricity transmission required to transport supply.
  - **Offshore hydrogen transmission** scales proportionally to electrolysers, while **onshore transmission** scales more significantly to accommodate North-to-South flows and exports.
  - **Offshore electricity transmission** scales primarily across offshore hubs accommodating increased supply, while **onshore transmission** scales more moderately.
    - Hydrogen and electricity transmission continues to scale up to deliver **optionality of supply**.

Hydrogen Exporter *assesses a future in which GB exports hydrogen to Continental Europe, equivalent to roughly 25% of domestic hydrogen demand (~100 TWh).*

Our analysis shows that, compared to ST, **Hydrogen Exporter builds**:

		Onshore	Offshore
Supply	Offshore wind	n/a	**+24 GW**
	SMR + CCS	**+8 GW**	n/a
	Electrolysers	**(6 GW)**	**+9 GW**
Transmission	Hydrogen transmission	**+19 GW**	**+9 GW**
	Electricity transmission	**+7 GW**	**+37 GW** (of which 70% represents offshore-to-offshore transmission)

#2 - The choice of future hydrogen storage location in Great Britain has an impact on hydrogen backbone design

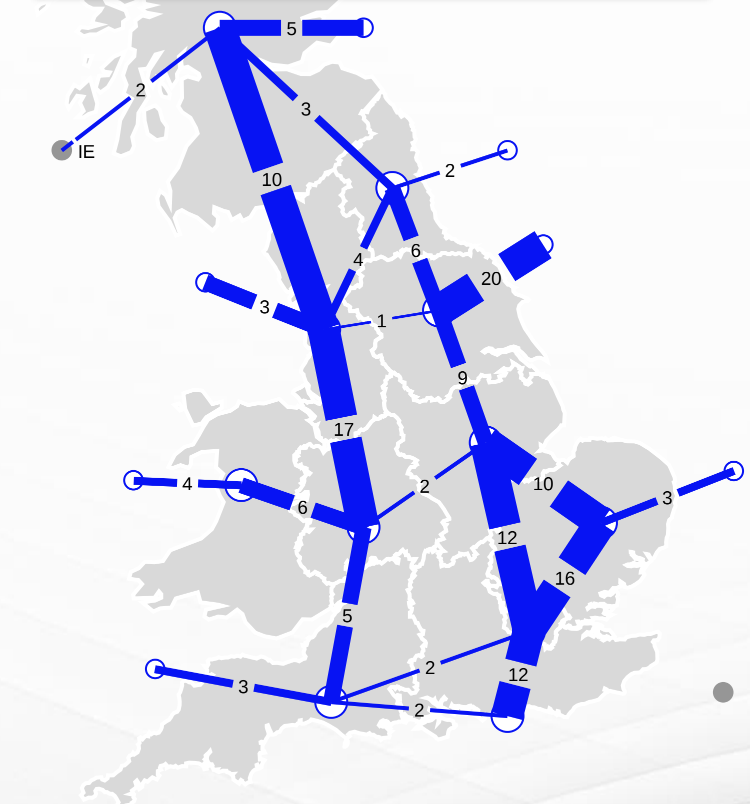
Limited Gas Storage assesses a future in which the Deborah gas storage facility is not developed on not converted to hydrogen.

2050 – ST

Bacton plays a key role in delivering hydrogen to London and the South-East

2050 – ST with Ltd Gas Storage

The country is **more reliant on North-South corridors** to deliver hydrogen



Key Messages

- **Infrastructure is sized according to peak demand**, and less about annual flows.
- Storage capacity is dispatched to meet peak demand at time of low renewable output. Thus**, its location has a critical impact of infrastructure build out.**
- **Deborah**, a large storage facility of 4.6bcm in East of England **has a critical impact on infrastructure** has it will be used to meet peak demand in London and the South of England.
- In a scenario where Deborah is not developed or not converted to hydrogen, the **GB becomes even more reliant on North to South flows.**

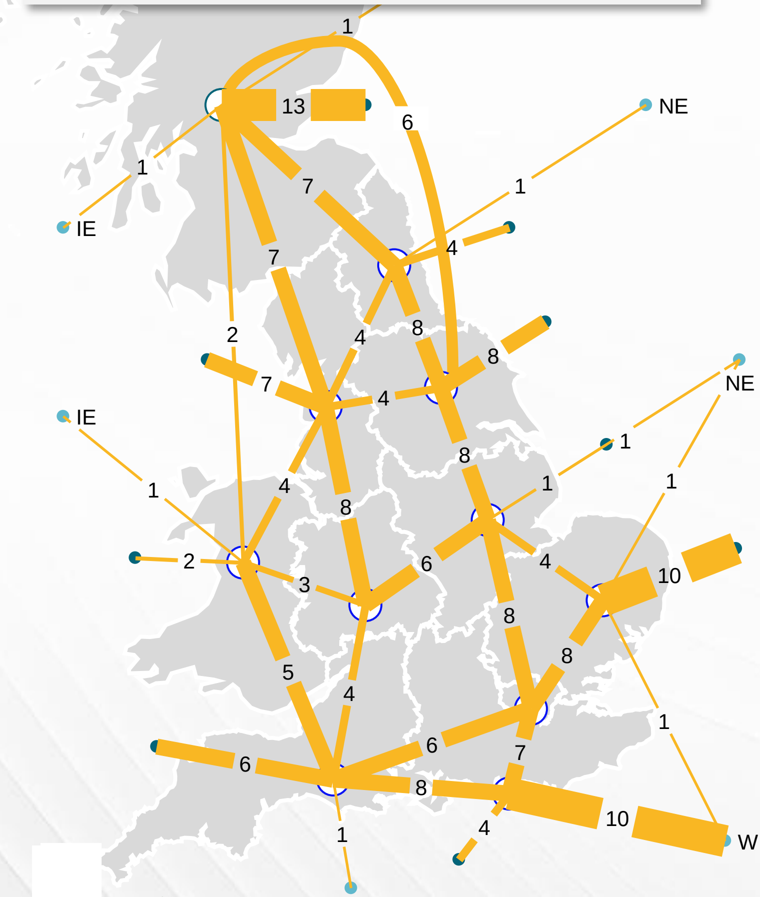
Note: (1) These maps presents a simplified representation of GB's future hydrogen transmission network defined by the nodal configuration used in this study and does not accurately reflect the real-world configuration of the existing natural gas network. (2) Transmission capacities reported in the map represent minimum operational capacity needs, and not rated nameplate capacities. (3) Analysis results may not align with planned hydrogen transmission investments, nor targets.

ST **CT** **LW**

#3 - In all three scenarios, electricity network develops in similar fashion, suggesting that a minimum level of future network expansion is required

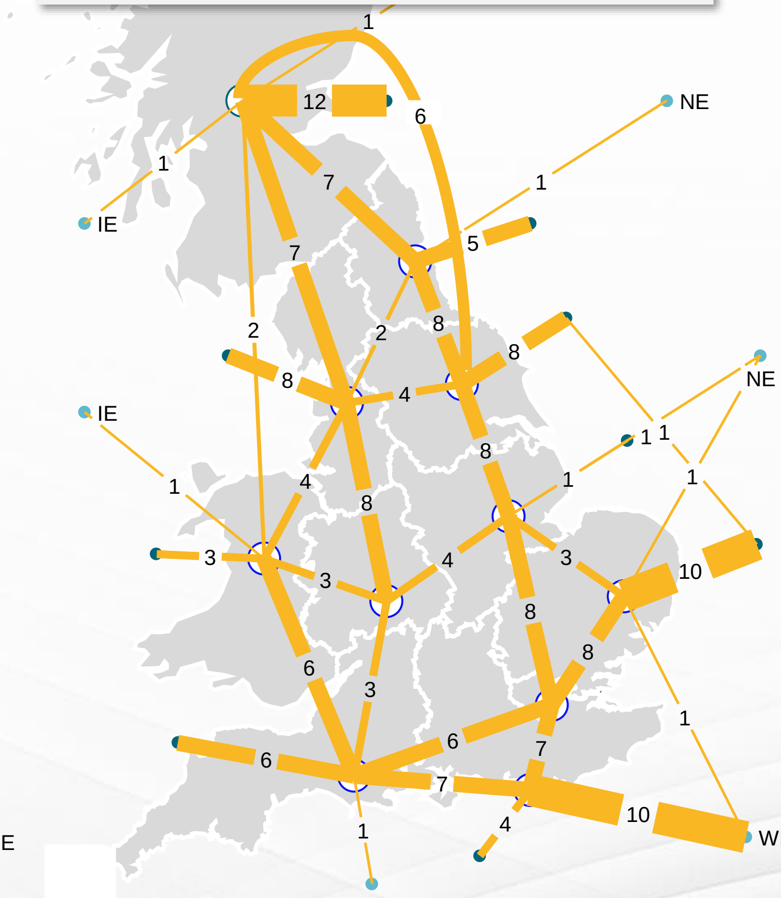
2050 - CT

Buildout of transmission network supports **doubling direct demand** by 2050 in CT.



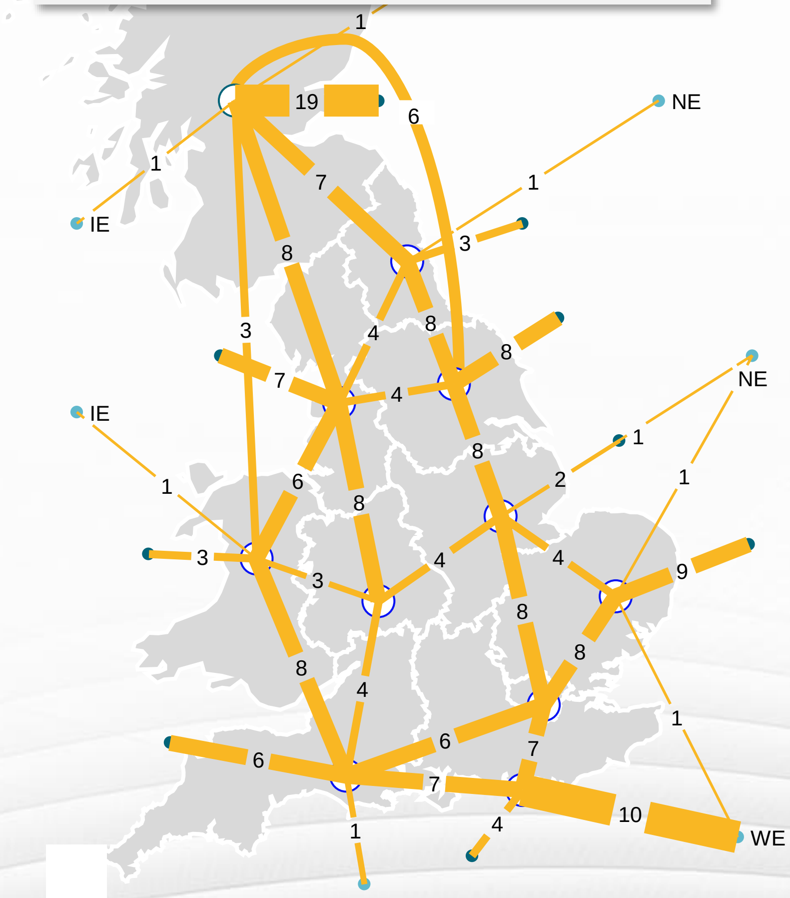
2050 - LW

Demand volumes are similar to CT in LW resulting in a **very similar electricity grid**



2050 - ST

With a higher indirect demand, grid design is similar but **increased Scotland importance**



Guidehouse Outwit *Complexity*

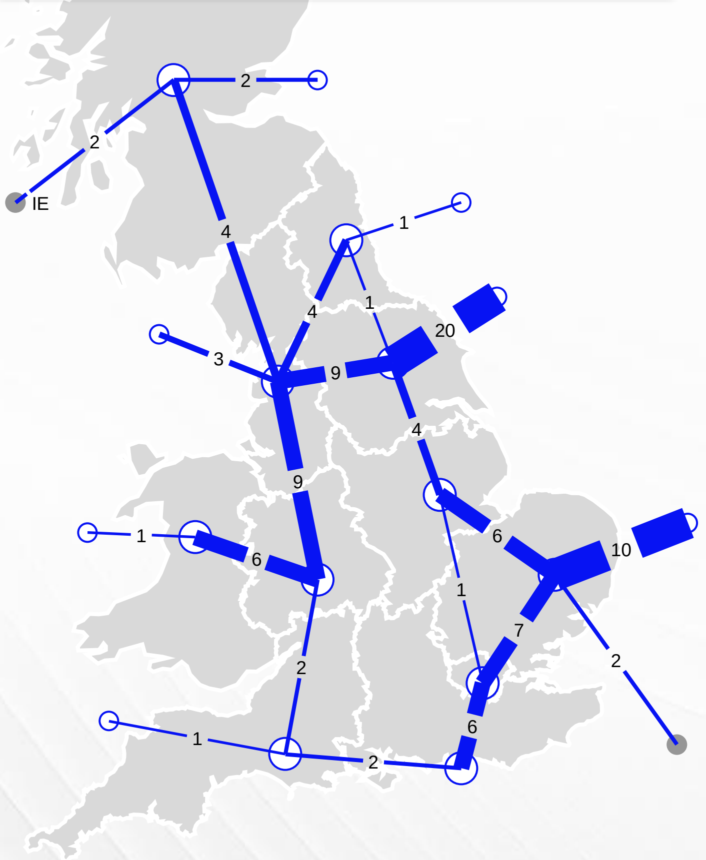
Note: (1) These maps present a simplified representation of GB's electricity transmission network defined by the nodal configuration used in this study and do not accurately reflect the real-world configuration of the network. (2) Transmission capacities reported in the maps represent minimum operational capacity needs, and not rated nameplate capacities. (3) Analysis results may not incorporate the latest planned or approved transmission and supply investments, nor recently-defined targets. (4) Holistic Network Design has not been considered; thus, capacity expansion may be different.

ST CT LW

#4 - A hydrogen network is developed across all scenarios, but network design and operation varies by scenario

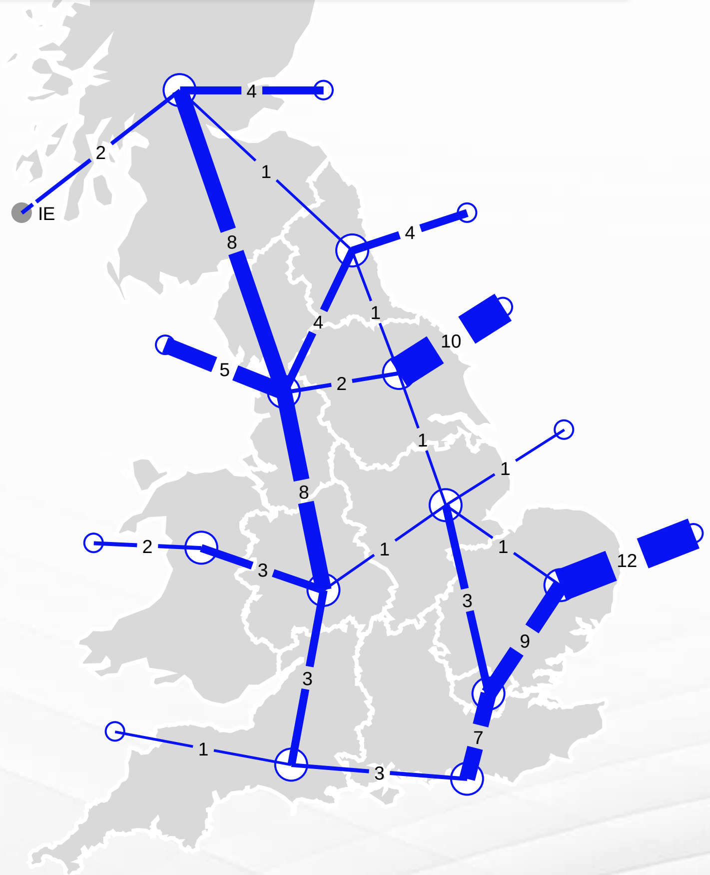
2050 – CT

Hydrogen network primarily **delivers hydrogen to H_2 GTs for electricity supply**



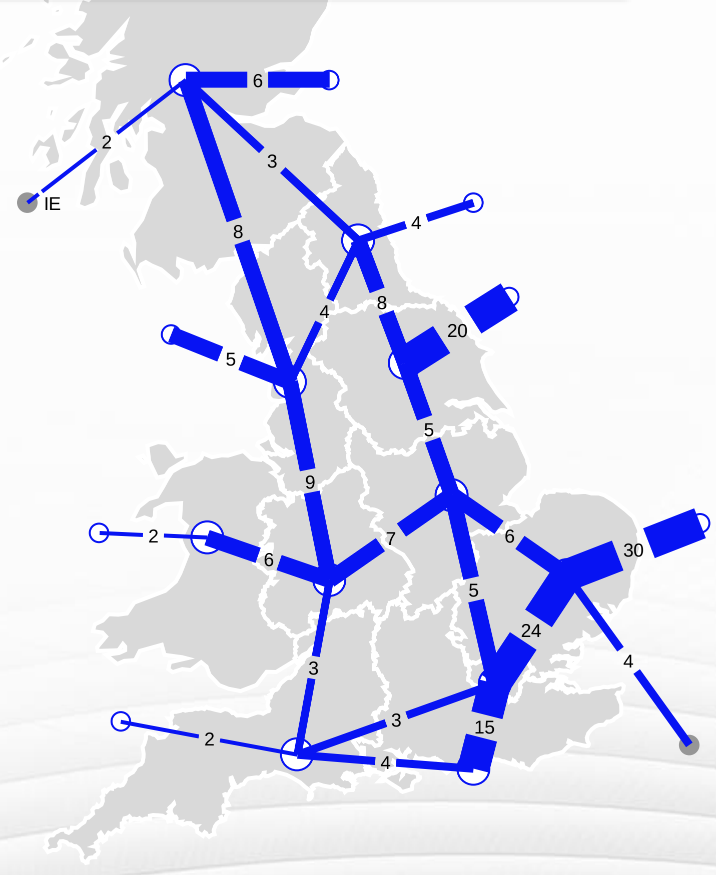
2050 - LW

Hydrogen network developed with the purpose of delivering **green H2** across GB



2050 - ST

Hydrogen backbone **connects hydrogen supply and demand.**



Note: (1) These maps presents a simplified representation of GB's future hydrogen transmission network defined by the nodal configuration used in this study and does not accurately reflect the real-world configuration of the existing natural gas network. (2) Transmission capacities reported in the map represent minimum operational capacity needs, and not rated nameplate capacities. (3) Analysis results may not align with planned hydrogen transmission investments, nor targets.

#5 - To highlight the benefit of integrated system planning, we modelled the evolution of an energy system with limited power and gas integration

General Modelling Approach

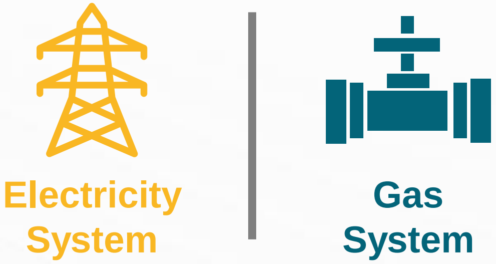
Limited Integration Sensitivity

- The expansion of **electricity supply** and the **electricity transmission network** is optimised **independently** of the gas system.
- The expansion of **gas supply** and the **gas transmission network** is optimised **independently** of the electricity system.

vs.

ST - Example of an integrated scenario

- The expansion of **electricity and hydrogen supply** and the expansion of **electricity and hydrogen transmission networks** are optimised as an **integrated, whole system**.



Examples

- **1 MW of green hydrogen capacity** is dedicated to meet hydrogen demand **OR** electricity production, but not both.
- **1 MW of offshore wind** is dedicated to meet electricity demand **OR** hydrogen production, but not both.

- **1 MW of green hydrogen capacity** can be used for both hydrogen demand **AND** electricity production.
- **1 MW of offshore wind** can be used for both electricity demand **AND** hydrogen production.

#5 - An integrated scenario (ST) achieves 10% reduction in total energy system costs compared to the Limited Integration scenario

Key Messages

- In **Limited Integration**:
  - **Electricity supply** is sized and located to meet electricity demand; and similarly, **hydrogen supply** is also sized and located to meet hydrogen demand.
  - **Electricity transmission infrastructure** is sized to dedicated electricity supply; and similarly, **hydrogen transmission infrastructure** is also sized to dedicated hydrogen supply.
- In **System Transformation**:
  - **Electricity and hydrogen supply** is sized and located considering demand of both energy carriers.
    - **This leads to avoided investments in supply.**
  - **Electricity and hydrogen transmission infrastructure** is sized considering energy supply can serve both electricity and hydrogen demand, depending on changing supply-demand conditions.
    - **This leads to additional investments in transmission infrastructure.**

Limited Integration *assesses a future in which the energy system develops independently for electricity and hydrogen, without a whole systems approach.*

Our analysis shows that, compared to Limited Integration, **ST builds**:

Transmission Infrastructure

+18 GW of electricity transmission infrastructure within GB.

+36 GW of hydrogen transmission infrastructure within GB.

Supply Capacity

-30 GW of electricity supply (offshore wind, hydrogen GTs)

-4 GW of hydrogen supply (SMR+CCS).

+£5 billion (+12%) **more investment** in transmission infrastructure

-£43 billion (-12%) **less investment** in energy supply

£38 billion (-10%) of energy system savings in an integrated system (ST Scenario)

Conclusions

What is covered:

- **Key takeaways** – Benefits of integrated gas & electricity infrastructure in the future
- **Gap analysis** – What is missing to unlock the full potential of whole system planning
- **Recommendations** – What is needed to realise the full benefits of whole system planning

Key takeaways

Conclusions

Across **all the modeled scenarios integrated electricity and hydrogen transmission infrastructure planning can realise savings,** especially in **System Transformation** where energy system **savings** of **£38 billion by 2050** are possible. Early investments common across the transmission networks are needed to realise these savings.

Electricity key takeaways

The modeling shows that the increasing regional supply-demand imbalances will require increased GB-wide coordinated approach to transmission network development to minimise system costs, over and above that is currently undertaken.

A geographically coordinated approach to transmission network development is needed to optimise and accommodate the transport of the unprecedented increase in electricity supply capacity in some regions such as Scotland with more than 100 GW of renewables installed capacity by 2050.

Curtailment could be greatly reduced in an integrated scenario with the introduction of electrolysis and storage with renewable generation, unlocking their full potential by providing optionality to the power produced.

In a limited integration scenario, introducing electrolysis, as well as other technologies into the energy mix has the potential to greatly reduce renewable generation curtailment. This can lead to reduced energy costs and greater investment incentives with more stable revenues for developers.

Harnessing the opportunities of weather-dependent renewable energy sources requires you to increase the role of demand side flexibility and dispatchable peak generation

The scale-up of weather-dependent renewable resources increases the importance of supply-side flexibility and demand-side flexibility resources.

Early strategic investments in electricity transmission infrastructure are needed today to accommodate for the increase in renewable generation and reduce it cost

Strategic, whole system investments in new transmission infrastructure will be needed in across the modeled project scenarios to support the development of renewables and meet demand across the country. Taking investment decisions promptly will allow for better network integration which will result in reduced power generation costs and attract investments to build the required supply capacity. This need resonates with other studies conducted in the past year, such as the Offshore Transmission Network Review, Network Planning Review and others.

Hydrogen key takeaways

From the project modeling the hydrogen imbalance shows a need for a GB-wide hydrogen network, the scale and design of which differs with each scenario.

The scale and design of the backbone differs depending on purpose and need for hydrogen. In a high hydrogen demand scenario, the backbone delivers low-cost hydrogen from regions with excess supply to regions with high demand. However, in a high electrification scenario, the backbone plays a key role in delivering hydrogen to H_2 Gas Turbines across the country

In a high hydrogen demand scenario, a GB-wide backbone delivers low-cost hydrogen from regions with excess supply to regions with high demand. However, in a high electrification scenario, the network is more limited playing a key role in delivering hydrogen to H2 Gas Turbines across the country

In System Transformation, a scenario with significant hydrogen demand, blue hydrogen plays a key role in 2030 and 2040 to meet a rapidly increasing demand. In 2050, while green hydrogen plays a dominant role, delivering low-cost supply and reducing electricity curtailment, blue hydrogen is still needed to provide weather-independent supply to meet the scenario’s important residential heating demand.

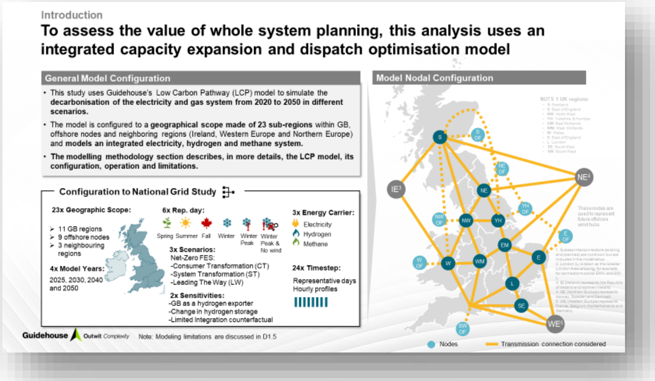
In all modelled scenarios, hydrogen storage is critical in supporting whole energy system demand during peak demand periods and low wind days

Hydrogen storage plays a critical role during high demand, low wind days, delivering up to 95 GW of firm, dispatchable supply and supporting both the gas and electricity systems. If Great Britain were to keep current gas storage volumes of 10TWh, hydrogen reserve would not last more than 5 days.

Strategically located investments in hydrogen transmission infrastructure are needed in the next decade to deliver the benefits of integrated system planning

Strategic, whole system investments in hydrogen transmission infrastructure are needed to support the development of renewable generation and meet demand across the country. Taking investment decisions promptly will allow for better network integration which will result in optimised energy generation and attract investments to build the required supply capacity.

Modelling outputs combined with stakeholder engagement inputs have been used to inform gap analysis and recommendations



Introduction

To assess the value of whole system planning, this analysis uses an integrated capacity expansion and dispatch optimisation model

General Model Configuration

- This study uses Guidehouse's Low Carbon Pathway (LCP) model to simulate the **decarbonisation of the electricity and gas system from 2020 to 2050 in different scenarios.**
- The model is configured to a **geographical scope made of 23 sub-regions** within GB, offshore nodes and neighboring regions (Ireland, Western Europe and Northern Europe) and **models an integrated electricity, hydrogen and methane system.**
- **The modelling methodology section describes, in more details, the LCP model, its configuration, operation and limitations.**

Configuration to National Grid Study

23x Geographic Scope:
- 11 GB regions
- 9 offshore nodes
- 3 neighbouring regions

4x Model Years:
2025, 2030, 2040 and 2050

6x Rep. day:
Spring Summer Fall Winter Winter Peak Winter Peak & No wind

3x Scenarios:
Net-Zero FES:
-Consumer Transformation (CT)
-System Transformation (ST)
-Leading The Way (LW)

2x Sensitivities:
-GB as a hydrogen exporter
-Change in hydrogen storage
-Limited integration counterfactual

3x Energy Carrier:
Electricity
Hydrogen
Methane

24x Timestep:
Representative days
Hourly profiles

Model Nodal Configuration

Guidehouse Outwit Complexity Note: Modeling limitations are discussed in D1.5

Who is in the room today?

nationalgrid
nationalgridESO
Gas Transmission
Department for Business, Energy & Industrial Strategy
ofgem
UK Power Networks Delivering your electricity
National Infrastructure Commission
Climate Change Committee
E3G
SEVERN TRENT
bbl company
WALES&WEST UTILITIES
sse
Gas Networks Ireland
New Futures Network
Imperial College London
RWE
Cadent Your Gas Network
Scottish & Southern Electricity Networks
Scottish Water
xoserve

And others…

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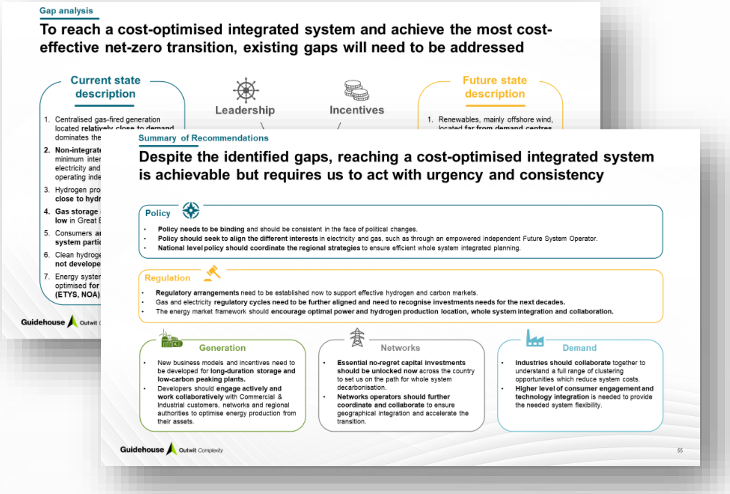

Gap analysis

To reach a cost-optimised integrated system and achieve the most cost-effective net-zero transition, existing gaps will need to be addressed

Summary of Recommendations

Despite the identified gaps, reaching a cost-optimised integrated system is achievable but requires us to act with urgency and consistency

Policy
- **Policy needs to be binding** and should be consistent in the face of political changes.
- **Policy should seek to align the different interests** in electricity and gas, such as through an empowered independent Future System Operator.
- **National level policy should coordinate the regional strategies** to ensure efficient whole system integrated planning.

Regulation
- **Regulatory arrangements** need to be established now to support effective hydrogen and carbon markets.
- Gas and electricity **regulatory cycles need to be further aligned and need to recognise investments needs for the next decades.**
- The energy market framework should **encourage optimal power and hydrogen production location, whole system integration and collaboration.**

Generation
- New business models and incentives need to be developed for **long-duration storage and low-carbon peaking plants.**
- Developers should **engage actively and work collaboratively** with Commercial & Industrial customers, networks and regional authorities to optimise energy production from their assets.

Networks
- **Essential no-regret capital investments should be unlocked now** across the country to set us on the path for whole system decarbonisation.
- **Networks operators should further coordinate and collaborate** to ensure geographical integration and accelerate the transition.

Demand
- **Industries should collaborate** together to understand a full range of clustering opportunities which reduce system costs.
- **Higher level of consumer engagement and technology integration** is needed to provide the needed system flexibility.

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Modeling work

Stakeholder Engagement

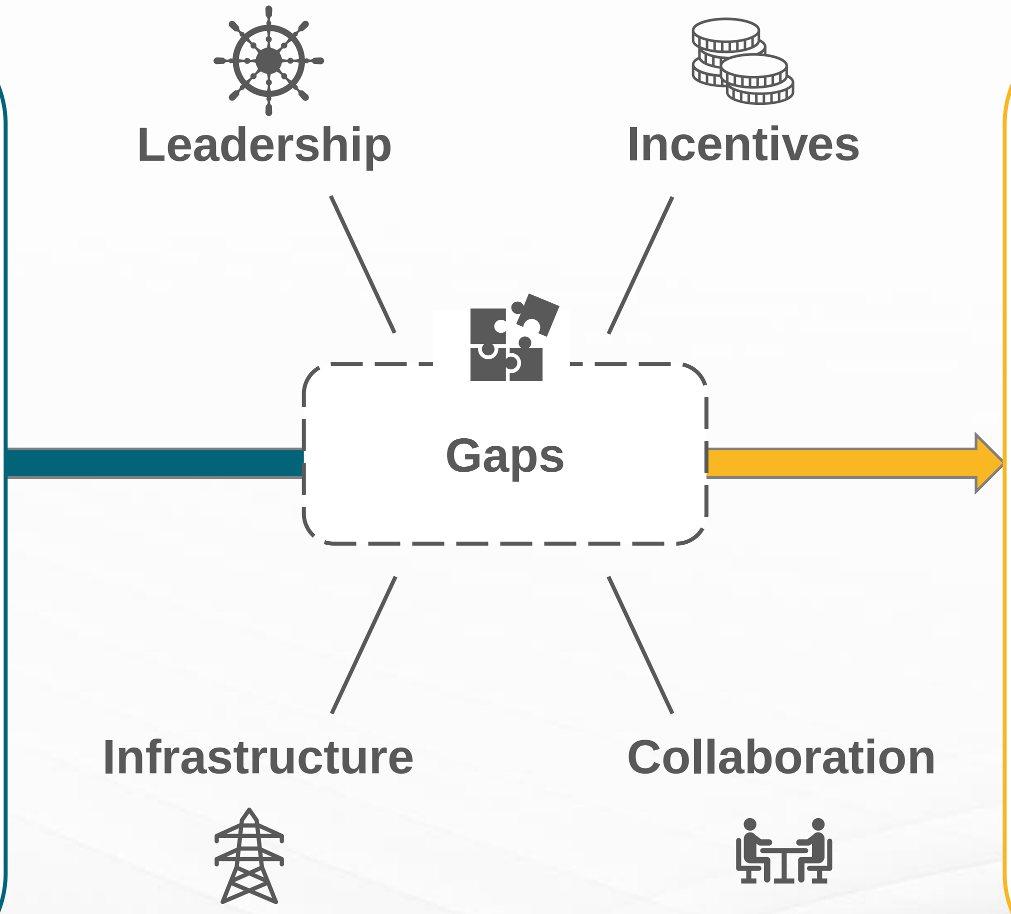
Gap analysis + Recommendations

Note: Guidehouse facilitated a virtual stakeholder event in October 2022 with 75+ industry stakeholders to discuss the benefits of whole energy system planning and identify key gaps and actions needed to address them. Several common themes emerged from the breakout discussions, which are briefly presented in the following slides (gap analysis) and were used (along with modeling outputs) to inform the recommendations.

To reach a cost-optimised integrated system and achieve the most cost-effective net-zero transition, existing gaps will need to be addressed

Current state description

1. Centralised gas-fired generation located **relatively close to demand** dominates the electricity mix
2. **Non-integrated energy system** with minimum interaction between electricity and gas systems, both operating independently
3. Hydrogen production is installed **close to hydrogen demand**
4. **Gas storage capacity is relatively low** in Great Britain
5. Consumers **are not active energy system participants**
6. Clean hydrogen technology market is **not developed and niche**
7. Energy system is planned and optimised **for the next ten years (ETYS, NOA)**.



Leadership

Incentives

Gaps

Infrastructure

Collaboration

Future state description

1. Renewables, mainly offshore wind, located **far from demand centres** dominate the electricity mix
2. **Fully integrated energy system** with power and gas/hydrogen network collaborating closely
3. Electrolysers are installed **close to large renewable hubs**
4. **Hydrogen storage capacity is large and plays a key role**
5. **High level of consumer - engagement** provides the system with additional flexibility
6. **Hydrogen market has been developed** and the fuel helps decarbonise transport & industries
7. Energy system is always **planned over multiple decades**

To achieve more specific future state goals, gaps need prioritising in areas including leadership, incentives, infrastructure and collaboration

Themes / Common areas

Leadership

#	Goal	Gap
1	Local and regional authorities are instrumental in helping GB achieve net-zero	Local authorities lack a clear mandate to drive the net-zero transition and sufficient funding to achieve that.
2	Several technologies incl. offshore wind, hydrogen and nuclear (among others) have an important role in GB's energy mix in 2050	Government has set ambitious targets for various technologies that will support the net-zero transition, however there is no detailed roadmap on how these targets could be met for each technology.
3	Whole system planning is always planned for the long-term and with consistency	Current political and regulatory landscape does not provide certainty required by market participants to accelerate the development of certain technologies.

Incentives

#	Goal	Gap
1	Household and industry have developed higher energy efficiency standards to reduce their energy demand	There is currently not sufficient incentives and communication articulating the need for household to invest in better insulation or more efficient processes.
2	High level of consumer engagement play a key role in reducing peak demand through DSR and V2G	Residential consumer engagement trials needs to be developed further and scaled up rapidly to most households in Great Britain.
3	A significant installed capacity of hydrogen turbines are peaking plant and support the electricity system at time of low RES output	The current peaking plant incentives' volumes fall short to attract the required capacity of peaking plants needed in 2050.

To achieve more specific future state goals, gaps need prioritising in areas including leadership, incentives, infrastructure and collaboration

Themes / Common areas

Infrastructure

#	Goal	Gap
1	The electricity grid more than doubles in capacity compared to today to accommodate for a rapidly increasing demand.	The current pace of new electricity transmission infrastructure investments is too slow to meet future network requirements.
2	A hydrogen backbone connects hydrogen production to demand across the country, allowing hydrogen production to be optimised	There is currently no gas hydrogen backbone today and no investments planned to support the optimal location of hydrogen production.
3	Hydrogen storage is large enough and located strategically to provide resiliency to both gas and electricity markets	GB's current gas storage capacity is relatively modest. In the future, significant new hydrogen storage will be an essential element to support the expected increase in weather-dependent generation and provide seasonal and daily resiliency for both gas and electricity markets.

Collaboration

#	Goal	Gap
1	Appropriate collaboration mechanisms support whole system planning are in place	Current market player internal structure (generators, industrials etc…) and network licence arrangement (utilities) do not foster collaboration across sectors.
2	Integrated whole system studies are the norm, not the exception	Whole system studies such as this report are still rare and may stall the realisation of whole system benefits. Different stakeholders (e.g., electricity/gas networks, system operator, government) develop their own studies
3	Investment timing and regulatory cycles are planned over decades and always coordinated across electricity and gas	Price control periods for electricity and gas distribution and transmission are not currently aligned and cover only a few years.
4	Data sharing is common practices across the energy industry	The current competitive and regulatory landscape between organisations do not foster data sharing as a standard practice

Despite the identified gaps, reaching a cost-optimised integrated system is achievable but requires us to act with urgency and consistency

Policy

- **Policy needs to be binding** and should be consistent in the face of political changes.
- **Policy should seek to align the different interests** in electricity and gas, such as through an empowered independent Future System Operator.
- **National level policy should coordinate the regional strategies** to ensure efficient whole system integrated planning.

Regulation

- **Regulatory arrangements** need to be established now to support effective hydrogen and carbon markets.
- Gas and electricity **regulatory cycles need to be further aligned and need to recognise investments needs for the next decades.**
- The energy market framework should **encourage optimal power and hydrogen production location, whole system integration and collaboration.**

Generation

- New business models and incentives need to be developed for **long-duration storage and low-carbon peaking plants.**
- Developers should **engage actively and work collaboratively** with Commercial & Industrial customers, networks and regional authorities to optimise energy production from their assets.

Networks

- **Essential low-regret capital investments should be unlocked now** across the country to set us on the path for whole system decarbonisation.
- **Networks operators should further coordinate and collaborate** to ensure geographical integration and accelerate the transition.

Demand

- **Industries should collaborate** together to understand a full range of clustering opportunities which reduce system costs.
- **Higher level of consumer engagement and technology integration** is needed to provide the needed system flexibility.

Clear and consistent policy is essential to shape the market toward the optimal energy system for consumers

Policy recommendation detailed description

- **Policy needs to be binding and should be consistent in the face of political changes**

To provide market with certainty and allow long-term planning which is critical to achieving the most cost-effective future energy system expansion described in this analysis.

- **Policy should seek to align the different interests in electricity and gas**

To steer the system toward the best outcomes for consumers and energy security.

- **Policy at the national level should coordinate regional strategies to ensure efficient whole system integrated planning**

Local and regional authorities can drive the transition to net-zero, however national policy should coordinate initiatives so that individual regions are not left too far behind.

Effective regulation covering emerging markets and plans for the long-term is key to shaping whole system planning

Regulatory and market recommendation detailed description

- **Regulatory arrangements need to be established to support effective hydrogen and carbon markets**

To provide structure to these nascent markets. More structure will provide the market participants with more confidence and certainty regarding their investments as well as with clear guidelines leading to better system integration.

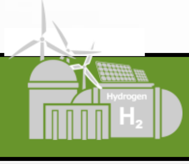
- **Gas and electricity regulatory cycles need to be further aligned and need to recognise investments needs for the next decades.**

To ensure that investments in both networks are coordinated and sufficiently integrated, as different investment timelines based on existing price control periods may impact the timing of whole system investment decisions. Regulation should also encourage communication between electricity and gas systems, overcoming existing limitations of existing licence conditions. Alignment of regulatory timelines could be a step towards this direction.

- **The energy market framework should encourage optimal power and hydrogen production location, whole system integration and collaboration.**

To ensure that market participants adopt a whole system integration approach, where business cases are aligned with system requirements, including. considering demand locations and other network infrastructure requirements (e.g., implement locational pricing)

Generation and storage capacity needs to increase significantly in the coming decades; new business models and collaboration and processes are needed



Hydrogen and electricity generation recommendation detailed description

- **New business models and incentives need to be developed for large-scale storage and low-carbon peaking plants**

To ensure that there are sufficient investments in large-scale storage capacity. As shown in this study, large-scale energy storage, particularly hydrogen storage, is key to effective whole system planning and to achieving a smooth transition towards more weather-dependent renewables in the future.

- **Developers should engage actively and work collaboratively with Commercial & Industrial customers, networks and regional authorities**

To better understand the system needs and investment timescales, which would provide more certainty to investors and reduce risks. Developers should be active in breaking the cycle of market uncertainties regarding the use of new fuels, such as hydrogen, leading to stagnation.

Energy networks are the backbone of the energy transition; essential low-regret capital investments should be unlocked now

Hydrogen and electricity network recommendation detailed description

- **Essential low-regret capital investments should be unlocked now across the country to set us on the path for whole system decarbonisation**

To ensure that the transition is not slowed down by the significant expansion required (as this study has shown) in both hydrogen and electricity transmission. This is particularly noteworthy as this study has highlighted that whole system integrated planning is dependent on a well interconnected gas and electricity transmission infrastructure. This would provide optionality to energy generation and reduce overall system costs.

Network operators should coordinate and collaborate to ensure geographical integration and accelerate the transition

To avoid unnecessary congestion and increased renewable energy curtailment due to lack of coordination between electricity and gas infrastructure. This is particularly relevant for regions that have high renewable energy generation potential such as Scotland, where this report expects 100GW+ of renewable energy capacity installed.

As consumers transition to low-carbon fuels, collaboration, clustering and high engagement are key to system optimisation

Hydrogen and electricity demand recommendation detailed description

- **Industries should collaborate together to better understand the full range of clustering opportunities which may reduce system costs**

To alleviate energy transportation constraints that might delay fuel-switching and thus, the net-zero transition. The first UK industrial clusters have demonstrated that aggregating demand for low-carbon fuels can attract early and increased investments, particularly in hydrogen production. Smaller industrials, cross-sector, should work together as well to find clustering opportunities.

- **Higher level of consumer engagement and smart technology integration is needed to provide the system with higher flexibility**

To support the energy system at times of low renewable energy output and high energy demand. This report highlighted that demand-side flexibility plays a key role in helping solve one of the major challenges that future energy system may face: high energy demand at times of low renewable energy output (e.g., a winter peak day with low wind). Greater demand-side flexibility also allows to make best use of the excess generation during high-wind, low demand days. Higher level of consumer engagement, both industrial and residential, could contribute to load shifting during the day resulting in cost savings (particularly on the peaking plants side). Smart technology integration is necessary to unlock high level of consumer engagement through automatization of use.

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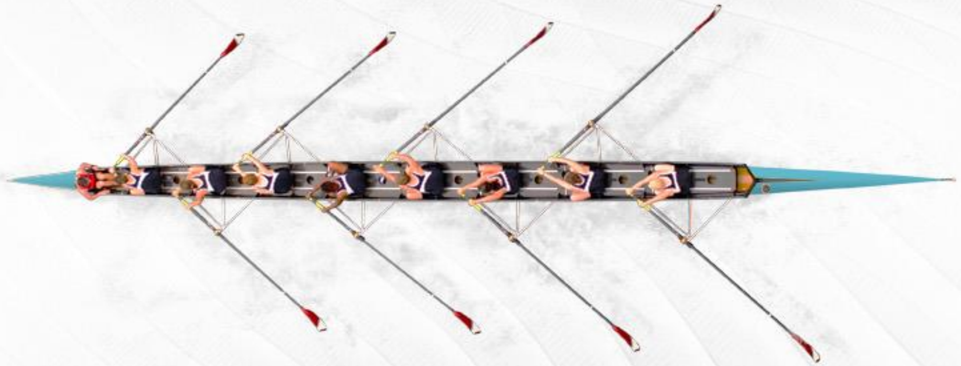

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