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	Name	Position
Author(s)	Dan Murrant, Hamzah Ahmed, Stuart McKinnon, Frank Bridge	Networks and Energy Storage Lead, (Technical Lead) Senior Power Systems Engineer (Subject Matter Expert) Senior Adviser, Whole Systems & Networks (Subject Matter Expert) Project Manager
Reviewer(s)	Richard Waine, Paul Guest, Ben Shafran, Jennifer Pride, Professor Jianzhong Wu	Hydrogen Networks Consultant (Subject Matter Expert) Practice Manager, National Energy Systems (Subject Matter Expert) Head of Markets, Policy & Regulation (Subject Matter Expert) Head of Energy Delivery/Climate Change, Energy and Planning Directorate/Welsh Government (Customer) School of Engineering at Cardiff University (Independent)
Approver(s)	Nicholas Geddes, Emma Harrison, Richard Halsey	Business Leader, Whole Systems and Networks (Project Assurance) Business Leader, Systems Integration (Technical Assurance) Capabilities Director, Innovation Department

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CONTENTS

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Report Structure

This is the Technical Report for the Future Energy Grids for Wales (FEW) project. It provides a summary of the report findings ('Recommendations for Welsh Government' and 'Network Implications') and the supporting evidence and analysis. A summary report in PowerPoint has also been published alongside this Technical Report.

The Technical Report is split into three main parts:

A. **Executive Summary:** a summary of the key findings, recommendations for Welsh Government and identified Network Implications.

B. **Insights and Evidence:** the evidence and analysis supporting the recommendations and network implications.

C. **Appendices:** further details on the approach taken to the project and project analysis.

PART A: EXECUTIVE SUMMARY

1. EXECUTIVE SUMMARY

1.1. CONTEXT

The Senedd Cymru has set the ambitious target for Wales to reach Net Zero greenhouse gas (GHG) emissions by 2050, contributing to the United Kingdom's (UK's) legally binding 2050 commitment. The Welsh Government rightly sees this as an opportunity to establish Wales as a global leader in climate responsibility; and in the technologies and businesses that will power the future. To maximise the benefits, Governments around the world have to carefully consider how to capture the economic opportunities and ensure a fair transition, whilst bringing citizens along on the journey and maintaining security of supply.

It is widely acknowledged that achieving these decarbonisation targets will require a fundamental change to the way the Welsh economy and energy system is structured and operated. This will require clear, long-term decisions around key enablers such as skills, infrastructure and planning. From an energy perspective, Net Zero will herald a fundamental change in how the Welsh (and Great British (GB[1])) energy system is planned, developed, integrated and operated, as the wide-spread adoption of new energy end-use, supply and flexibility technologies deliver fundamental change.

As key sectors such as heat and transportation decarbonise, natural gas consumption will fall significantly and electricity demand rise. As technologies such as onshore and offshore wind, and solar generation come online, the location of supply will become more decentralised or located further from consumption, and require different types of storage and flexibility technologies.

Energy networks are the connective tissue which link supply, storage, flexibility and demand – so as the type and location of the other energy infrastructure changes, so too will the network infrastructure, ahead of need. The electricity, heat and natural gas networks and the operators and decision-makers that determine their future, will be fundamental to Wales's decarbonisation and economic ambitions. Network infrastructure needs to be available at the right time and in the right place to connect new sources of energy supply and meet end-use demands.

The future of the natural gas grid is uncertain but is likely to be very different from today. Whilst natural gas consumption will fall dramatically, hydrogen will be an important zero-carbon option for some hard to decarbonise sectors (e.g. high-temperature industrial processes, dispatchable electricity generation) and could play a role in other forms of transportation (e.g., shipping) and managing peak heating in a Net Zero future. However, hydrogen volumes and the end-use demands it will service remain uncertain in key areas.

The outlook for electricity networks is very different with widespread acknowledgement that rapid, sustained, anticipatory investment is needed, as key sectors electrify away from oil (e.g., transportation) and natural gas (e.g., heating). The key uncertainty for electricity transmission and distribution networks is when, where and how much to reinforce, as the scale, timing and nature of key technology adoption (e.g., electric vehicles (EVs), heat pumps, offshore wind) remains somewhat unclear.

Too much electricity grid reinforcement in the wrong places for the wrong technologies can lead to stranded assets, resulting in unnecessary cost to the consumer. However, insufficient anticipatory

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[1] In this report UK and GB appear to be used interchangeably, however Northern Ireland's electricity and natural gas networks are separate from that of GB. As this project is focusing on energy networks in Wales, this project generally refers to GB, although UK is used where appropriate, for example in the case of the UK Government.

investment will perpetuate the challenges seen today with grid connections at risk of taking over 10-years for large scale renewable developers; and record constraint payments being made to generators already on the grid. Both issues act to the detriment of citizens. Taking timely decisions, typically under conditions of uncertainty, is especially important given reinforcement network build times can be over a decade[2].

So, the problem is challenging. Network capacity is needed ahead of time to link new low carbon energy supplies and demands; there is a range of uncertainties in the underlying drivers of network investment (e.g., rate and extent of adoption of key technologies); and investment lead times are long.

This is exacerbated by the current energy network governance, institutional, and decision-making architecture. The Net Zero transition challenge is a whole system one, but network planning is undertaken by different transmission and distribution companies, each different for the electricity and natural gas sectors. Network plans are also assessed at different times as there is an offset between the price control processes for different parts of the networks, making assessment by the regulator even more difficult.[3]

This makes arriving at a whole system network solution challenging for network operators and their regulator Office of Gas and Electricity Markets (Ofgem). Unlocking these network decisions and investments however is crucial for the Welsh energy system and economy. A "wait and see" approach is not sufficient when the pace and scale of the Net Zero challenge is so significant. The importance of meeting this challenge, in the short and medium-term, is increasingly well recognised across the sector, with several initiatives already in motion to address key aspects. For example:

- The Department of Energy Security and Net Zero (DESNZ) appointed Nick Winser as the Electricity Networks Commissioner (ENC) to identify options to reduce the time it takes to identify the need for and build onshore electricity transmission assets.
- National Grid Electricity System Operator's (NGESO) Holistic Network Design (HND) has informed Ofgem's new regulatory approach for Accelerated Strategic Transmission Investments (ASTI)[4].
- Ofgem's Future System Network Regulation (FSNR) consultation[5] on the post RIIO-2 price control structure, is considering how to enable the necessary anticipatory electricity network investment and enable whole systems network planning.
- The creation of the Future System Operator (FSO) under the Energy Bill[6] passing through the Houses of Parliament will bring NGESO into public ownership and give it responsibility for whole system network planning and operation.

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[2] It is estimated that it currently takes 11- to 14-years from transmission asset needs identification to operation. This includes planning, regulatory, design, procurement and energisation processes.
[3] The current electricity transmission, natural gas transmission and natural gas distribution network price controls (RIIOET2, RIIO-GT2 and RIIO-GD2 respectively) run from 2021 to 2026, and the current electricity distribution price control (RIIO-ED2) runs from 2023-2028.
[4] Decision on accelerating onshore electricity transmission investment, Ofgem ASTI decision (2022) (https://www.ofgem.gov.uk/publications/decision-accelerating-onshore-electricity-transmission-investment)
[5] Consultation on frameworks for future systems and network regulation: enabling an energy system for the future, Ofgem (2023) https://www.ofgem.gov.uk/publications/consultation-frameworks-future-systems-and-network-regulation-enabling-energy-system-future
[6] Energy Bill [HL], UK Parliament (2022) https://bills.parliament.uk/bills/3311

- Ofgem's consultation on the Future of Local Energy Institutions and Governance[7], proposes introducing Regional System Planners (RSPs) to ensure electricity and natural gas Distribution Network Operators (DNOs) produce coherent plans.
- The current RIIO-ED2 price control requires DNOs to take a whole systems perspective.
- The Centralised Strategic Network Plan (CSNP)[8] in the future will identify if further reinforcements will be required to support future generation connections.
- DESNZ's Review of Electricity Market Arrangements (REMA) is considering new market arrangements to, amongst other things, deliver better locational signals to energy generation and storage assets connected and connecting to the electricity grid.

The Welsh Government, conscious of the centrality of network investment to its economic and decarbonisation ambitions, is also seeking to understand and identify ways in which it could help alleviate these challenges in Wales. It appointed the Energy Systems Catapult (ESC) to deliver the Future Energy Grids for Wales (FEW) project.

ESC whole energy system modelling capabilities were used in this project to examine future energy systems, and trajectories towards them. The FEW project aimed to:

- Consolidate a broad view, across the network companies operating in Wales, of the Net Zero compliant Welsh future energy system pathways to 2050;
- Identify the key implications for electricity and gas network operators and steps needed to develop energy networks in Wales as part of the wider UK energy system; and
- Develop recommendations for the Welsh Government to take forward, consistent with its ambitions to accelerate decarbonisation and role in the energy governance landscape.

(For the full project aims and objectives see Appendix A)

Ensuring the Welsh energy system meets Net Zero is a complex challenge, with multiple layers of governance and regulation. Therefore, not all legislative and regulatory levers are in the control of one actor. Ofgem, the UK government, and the network and system operators all have a role to play alongside the Welsh Government.

The Welsh Government can play a crucial role using its devolved powers (e.g., local planning); convening parties (e.g., Local Authorities, developers, network companies), engaging Welsh citizens and businesses; demonstrating leadership; and bridging gaps within and between different planning structures (e.g., spatial and Local Area Energy Plans (LAEPs)). Whilst other organisations will have direct powers in other areas (e.g., Ofgem on network price controls), the Welsh Government can play a crucial leadership role in representing the Welsh whole system needs, and unlocking network investment and the Net Zero transition.

[7] Consultation: Future of local energy institutions and governance, Ofgem (2023) https://www.ofgem.gov.uk/publications/consultation-future-local-energy-institutions-and-governance
[8] Network Planning Review (NPR), NGESO https://www.nationalgrideso.com/future-energy/projects/network-planning-review-npr

1.2. APPROACH

Given the transition uncertainties noted above and the challenge this creates for network infrastructure investment, the FEW project used scenarios and whole energy system modelling to provide a strategic view of the potential 2050 Net Zero transition pathways for Wales, nested in and consistent with the transition of the rest of the UK. This modelling provides a long-term perspective to identify strategic network implications and recommendations for Welsh Government. Strategic whole system modelling can provide a view of the kind of energy system networks may need to enable and identify areas of uncertainty and greater certainty, such as vectors or technologies that are needed regardless of variations in the scenarios modelled. However, it cannot identify the specific network upgrades that come from network planning, and are required to justify investment decisions – this must come from network companies.

These scenarios are not predictions, but least-cost energy system designs, that achieve Net Zero and interim carbon budget targets with given security of supply standards. Given their long-term time horizons and strategic nature, they can provide a credible high level, whole system view. They do not evaluate all specifics such as business cases for investment; they are however highly valuable tools that can be used to aid decision making under uncertainty.

There are clearly significant uncertainties in the future of the energy system in Wales and the wider UK. These are not just technical uncertainties: policy, consumer behaviour, societal trends and the economy also play a significant role. The key to delivering Net Zero is enacting decisions in the real-world, which can be usefully guided by long-term techno-economic modelling.

The FEW project was delivered using a combination of whole system modelling; a review of existing evidence; and engagement with the networks operating in Wales, Ofgem and Welsh Government, as well as briefings with a broader set of stakeholders (e.g., Citizens Advice, Farmers Union Wales) The overarching approach is summarised in Figure 1.

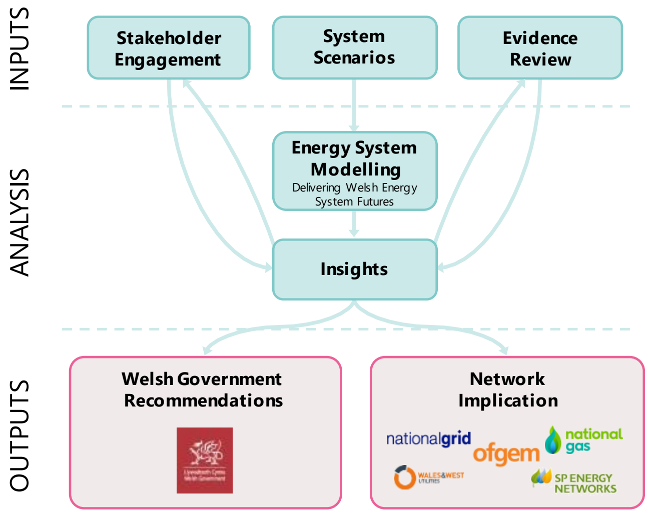


Figure 1: Project Approach

Two baseline whole energy system scenarios were developed for Wales called 'Technology-Optimistic'[9] (TOC) and 'Societally Optimistic'[10] (SOC)[11], with scenario assumptions agreed in consultation with the network companies, Ofgem and Welsh Government. The assumptions used in the Technology-Optimistic scenario are built around a narrative that there is success in technological innovation. Whereas the Societally Optimistic scenario places more emphasis of consumer awareness and engagement, leading to proactive demand reduction, and nature-based carbon abatement (e.g. afforestation). Sensitivity scenarios were then used to investigate variations of single factors on these two baseline scenarios. 42 sensitivity scenarios (See

[9] TOC is built around the narrative that there is success in technological innovation, which delivers emissions abatement technologies and resources (e.g., biomass, enhanced capture rates from CCS, and direct carbon capture).

[10] SOC is built around the narrative that consumer awareness and engagement leads to proactive demand reduction (e.g., slower growth in aviation, and dietary change).

[11] For full details of the scenarios see section 2.2.1.

Appendix C) were developed, to test a variety of energy system questions, which allowed the impact of key risks and uncertainties to be assessed.

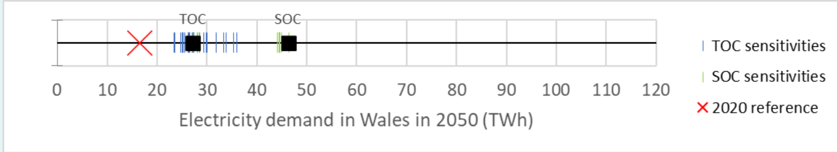
ESC's Energy System Modelling Environment (ESME) (See Appendix C) was used to undertake modelling. It is a UK-wide strategic whole energy system model with 12 onshore modelled "regions" and 13 offshore regions. It models the whole UK energy system and allows the extraction of results for individual modelling regions, one of which is the country of Wales. The 42 sensitivity scenarios then provided the basis to develop insights about the Welsh energy system, to test with stakeholders and in turn identify key strategic network implications and recommendations for Welsh Government. Further details of the approach taken is in Appendix A.

1.3. WELSH ENERGY SYSTEM FUTURES

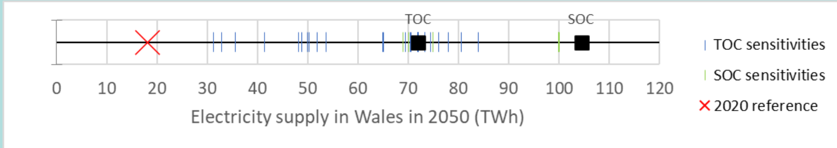
The modelling of the baseline scenarios and sensitivity scenarios resulted in a broad range of possible Welsh energy system futures. These show areas of the energy system where modelling assumptions and sensitivities have led to commonality, and where there is more range and uncertainty.

Table 1 shows the variation of some of the key modelling outputs across these different futures. Further detailed analysis of the energy system futures is included in section 3 onwards of this report. The resulting Welsh Government recommendations and network implications are listed in sections 1.5 and 1.6 of this Executive Summary, however, some high-level observations can be made about the range of results across the scenarios. These are presented next to the charts in Table 1 and further analysis is noted in section 1.4.

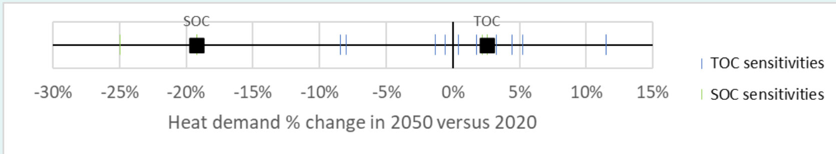
Electricity demand: The electrification of heat and transport lead to a significant increase electricity demand in Wales. Although typically a low demand scenario, the modelling of a Societally Optimistic future suggests a higher demand due to an increase in hydrogen production via electrolysis, with a particularly significant increase during the 2040s.



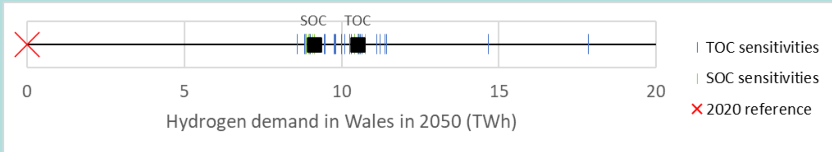
Electricity supply: Uncertainties around support for generation result in a broader range of potential sources of electricity supply in Wales in 2050. In most cases, annual generation in Wales is greater than demand, indicating net export to rest of GB. A Societally Optimistic future sees highest electricity production due to the deployment of a substantial nuclear capacity at Wylfa, which contributes to exports to the rest of GB.



Heat demand: Heat demand in Wales is ~14TWh in 2020[12], with electrification as the primary energy supply source in 2050. The key challenge is managing peak heat, which drives much of the distribution network reinforcement requirement. An increase in population leads to a slight rise in demand in a Technology-Optimistic future, despite some efficiency gains from insulating homes. In a Societally Optimistic future there are similar levels of home insulation, but heating demand is lower due to behaviours such as shifting and reducing demand (whilst still being thermally comfortable).



Hydrogen demand: Under the majority of scenarios there will be an important role for hydrogen in the 2050 energy system, with around 10TWh of demand being met by hydrogen. This is driven largely by hydrogen in shipping and some industrial processes, and smaller demands from power generation and heating. Although total hydrogen demand is seen to increase to nearly 18TWh in one sensitivity.



Gas demand: Some demand for natural gas is retained for industry and shipping. The more technologically advanced Carbon Capture Utilisation and Storage (CCUS) options in the Technology-Optimistic future allows for a greater role for natural gas with CCUS in industry. This leads to a greater total natural gas demand in 2050 compared to a Societally Optimistic future.

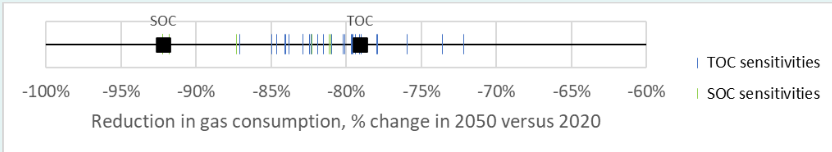


Table 1: Scatter charts showing the variation of modelling outputs across the baseline and sensitivity scenarios. Each chart has the baseline scenarios represented by a square (labelled TOC or SOC), surrounded by the sensitivity scenarios, depicted as vertical lines (TOC are green, SOC are blue). In some instances, there is a red "X" which represents the 2020 modelled baseline.

[12] Because of unusual changes to demand and generation in 2020 due to Covid-19, rather than presenting reference quantities referring to 2020 outturn energy trends, modelled trends for 2020 are shown. These are based on a hypothetical year absent all changes in demand due to Covid-19 and are included purely as a guide to future trends in energy consumption and production.

1.4. SUMMARY FINDINGS

There are several plausible pathways to decarbonise the Welsh energy system, in terms of future energy demands and technology deployment. Each requires extensive change to the Welsh and wider GB energy system, across different vectors and involving network operators, households, industry, and local and national Government bodies. Many of the changes needed to meet Net Zero need measures to be implemented in the very near-term to unlock other investments. For example, network infrastructure investment has a long lead time, while many of the enabling conditions such as developing skills and creating the right market frameworks can also take years.

This project found that many of the system changes are common across all the scenarios analysed. The importance of electrification in meeting Wales's heating and mobility needs in a Net Zero Welsh future is a common feature, along with the associated need for significant and rapid reinforcement of both electricity transmission and distribution networks. Increased renewable generation, including up to 11GW of offshore wind by 2050 connecting to Wales from the Celtic Sea[13], and an increase in electricity exports to the rest of GB, is another key common feature across the scenarios – this is likely to drive the need for significant transmission level reinforcement.

One common challenge identified across the different energy system futures relates to the difficulty of meeting peak heat demands. The analysis suggests that whilst electrification meets the majority of annual building heat demand (up to 8TWh and 70% of total building heat demand, by 2050), electricity infrastructure and generation requirements mean it is not cost effective to meet all demand at peak times via electricity. Although various additional technology options are selected, in part to help manage peaks, in some cases their low utilisation across the year indicates that understanding, managing, and meeting peak heat demands is an important priority.

Whilst some system changes were common throughout the energy system futures modelled, other changes were specific to one, or a small number of futures, based on different demand and technology assumptions. This demonstrates the impact of uncertainty in key areas. Specifically, volumes of hydrogen production and export as well as the scale of different hydrogen production technologies were found to vary significantly between scenarios. These differences can have ripple effects on the energy system, influencing aspects such as electricity demand and production, such as the case of green hydrogen, and the need for a hydrogen transmission network. The decisions made by large industrial sites regarding the vectors they choose to transition to for process decarbonisation also have broader implications for the energy system, with the choices contributing to an overall increase in demand for the selected vector.

With regard to areas not represented in the modelling there are other key conclusions to emerge from the project around how to realise the transition in the real-world.

Whilst it is relatively simple to use modelling tools such as ESME to develop least-cost energy system blueprints, delivering them and the associated network infrastructure in reality is far more challenging, with greater complexity, and institutional and governance silos to navigate. The need for whole system network planning to minimise transition costs, as well as the need for coordinated planning and investment across industry, civil society and networks will be an important step in delivering the transition efficiently. This work, the Welsh Government's own Renewable Energy

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[13] There may be additional capacity in the Celtic Sea connecting elsewhere, and capacity in the Irish Sea connecting to Wales. This is discussed further in section 10.2.1.

Deep Dive[14] and Ofgem's recent consultations[15] all reinforce the need for whole system network planning.

Whole system network planning ensures strategic coordination between different energy network vectors (electricity, natural gas, heat, hydrogen), to meet the future needs of the diverse range of energy users. It should minimise cost and maximise innovation and the value of new infrastructure, preventing future stranded assets. A small scale example of the whole system planning philosophy, is the heat network between the E.ON gas power station and the neighbouring National Grid Liquefied Natural Gas (LNG) terminal at Isle of Grain. The power station had a cooling requirement and a need to remove waste heat, whilst the LNG terminal required heat to return the liquid gas to its gaseous state. Building a heat pipe between the two sites recognised the needs of both sites and found a single solution providing benefit to both[16]. This is a small example of what might be required at a national network level.

Local Area Energy Plans (LAEPs) will be a key input into whole system network planning. Welsh Government is supporting all its Local Authorities to produce LAEPs and it is important that the value of this information is maximised. The process for how LAEPs are rationalised and brought within a coherent, whole system, network planning process for Wales is under development but will need further work and collaboration if it is to materially influence network planning and investments across Wales.

Welsh Government could not only use LAEPs to convene investors, developers and community groups to deliver them, but could also become the first country to push locally led energy planning into other levels of the energy system. This includes distribution and transmission network planning across vectors, including heat networks, as well as influencing decision-making at the UK Government level. Gaining agreement between the large number of energy system actors on how to use this information efficiently and effectively to streamline the planning and investment processes should be a priority and could form a strong competitive advantage for Wales.

Some areas are however less clear and will require further work to better understand. For example, there is uncertainty on the extent and role that flexibility, smart local energy systems and hydrogen for heating will have in the future energy system in Wales. This uncertainty stems from both the variations in the modelling outputs across the sensitivities and the fact that consumer behaviour, the practicalities of network changes and industrial vector switching remain relatively unknown. These conclusions have been informed by the wider analysis undertaken in this project (i.e., stakeholder engagement, literature reviews, etc).

Other factors which can influence the transition by either incentivising, or not, the adoption of specific energy technologies or services include Local Energy Markets (LEMs) and market design choices (e.g., Contracts for Difference (CfD) and any future role of Locational Margin Pricing

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[14] Renewable energy deep dive: recommendations, Welsh Government (2023) https://www.gov.wales/renewable-energy-deep-dive-recommendations

[15] Consultation: Future of local energy institutions and governance, Ofgem (2023) https://www.ofgem.gov.uk/publications/consultation-future-local-energy-institutions-and-governance ; Consultation on frameworks for future systems and network regulation: enabling an energy system for the future, Ofgem (2023) https://www.ofgem.gov.uk/publications/consultation-frameworks-future-systems-and-network-regulation-enabling-energy-system-future

[16] Isle of Grain Combined Heat and Power (CHP) Station, Kent, United Kingdom, Power Technology (2023) https://www.power-technology.com/projects/isleofgrain/

(LMP)[17]). Market design is an area still under consideration by the DESNZ and so is not discussed in detail in this report, however these decisions could be very powerful in shaping the evolution of the energy system and networks. The recommendations emerging from this work identify areas where Welsh Government can drive forward further action to better understand and account for the uncertainty inherent in the system.

1.5. WELSH GOVERNMENT RECOMMENDATIONS

The FEW project has identified recommendations for Welsh Government to support the networks and the wider Welsh energy system in its transition to Net Zero. This section provides a summary of the recommendations identified through the project analysis – the supporting evidence for the recommendations is provided in the 'Insights' sections (see section 3 onwards).

Recommendation 1: Accelerate key enabling conditions (e.g. skills and regional supply chain) that expedite the implementation and uptake of technologies that support the changes needed to transition to a Net Zero energy system.

As the energy system transitions to meet Net Zero, there will be widespread change to the type of energy consumed. Electricity consumption will increase significantly and potentially double with the electrification of key sectors (e.g., heat and transport) – a significant amount of this occurring in the next ten to fifteen years[18]. Natural gas consumption could reduce by over 85%, largely by 2040, with residual demand coming predominantly from natural gas with CCS for industrial processes.

The scale and opportunity of the transition and the skills, investment and work required to deliver it is vast, and it must occur at pace if intermediate carbon targets are to be met. Welsh Government should continue to create the wider environment needed to facilitate this scale of change, such as skills development (e.g., engaging with training providers), citizen engagement, publication of information, enabling access to data, and the development of Welsh supply chains. Whilst the Welsh Government may not have all the direct levers within its gift to deliver the transition, it can continue to play a vital role in creating the wider enabling environment.

Recommendation 2: Support energy networks to plan and invest for the Net Zero energy transition, particularly through the coordination of Local Area Energy Plans (LAEPs).

Peak electricity demand is the key driver of network capacity requirements. Welsh Government should work with Local Authorities and engage with network operators to ensure that LAEPs, which should be developed by next year across Wales, are coordinated at a regional level. They should also promote investment of new low-carbon technologies, whilst minimising increases in peak electricity demand. This could be through implementation of demand side interventions (see Recommendation 8), or by ensuring electrified heating options are supported by other technologies, to assist in meeting peak heat demand (see Recommendation 3).

The creation of Local Energy Markets (LEMs), which coordinate the operation of decentralised energy resources (e.g., renewable energy generators, storage and demand side intervention providers) within a confined geographical area (usually at distribution level), could help to reduce

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[17] Further information on Locational Margin Pricing is available on ESCs website (ESC - Locational Energy Pricing In The GB Power Market), with both Ofgem and National Grid ESO expected to publish assessments of LMP in the coming months.

[18] A total of 9TWh and 7TWh of consumption electrifies between 2020 and 2035 in Technology-Optimistic and Societally Optimistic scenarios.

peak demands, as they incentivise a flexible and smarter local energy system. Welsh Government should build on the work of existing trials such as the South Cornelly LEM in Bridgend to understand the role of LEMs and next steps in demonstrating and scaling-up.

Recommendation 3: Support the acceleration of heat decarbonisation across Wales through electrification and other low carbon heating technologies.

The analysis carried out in this project suggests that in cost effective, decarbonised energy systems, electrification continues to increase from today, meeting as much as 8TWh (70%) of annual Welsh building heat demand by 2050. Welsh Government should support the electrification of heat through a planning policy which encourages electrified options in new buildings, and skills and supply chain development (e.g., heating engineers). In social housing, support should be given for housing decarbonisation programmes (e.g., targeted retrofit and electrification). Electrification of heat in existing buildings will be a major long-term transformation and needs acceleration in the near term in priority areas. This can be informed by Wales's LAEPs.

However, meeting all Welsh building heat demand, particularly the peak heat demand via electrification may not be cost-effective due to generation and electricity infrastructure requirements. Welsh Government should actively engage with both electricity and gas networks to address the challenge of meeting peak heat demand, working to understand the local barriers and solutions to meeting future heat demand, and engaging with citizens to inform them of the benefits of any solution taken forward.

Welsh Government, in coordination with Local Authorities and through the implementation of LAEPs, should work to identify opportunities for alternative heating technologies. This should include, in particular, heat networks, but also other technologies (e.g., thermal storage and hybrid hydrogen systems) that support electrification through the management of peak demand. Welsh Government should continue to explore the potential of heat networks in Wales and could take a similar approach to the 'heat network zoning' that is being trialled in England[19] and is currently being taken forward in the Energy Bill[20].

The outputs from this work via the LAEP process, combined with the Welsh Government's Heat Strategy should be used to reduce network planning uncertainty by setting a vision for the future of heat in Wales. Reducing uncertainty can help create an environment where electricity and heat network companies can build the infrastructure required to support heat decarbonisation, ahead of need.

Recommendation 4: Welsh Government should work with industry to identify, develop and target industrial decarbonisation options, and support the creation of an enabling environment for change.

Welsh Government, electricity and natural gas networks, and heat network providers should continue to work with Net Zero Industry Wales (NZIW) and other industry representatives to assess identified decarbonisation options for industry and identify key industrial decarbonisation drivers. Ensuring this engagement process is open to all stakeholders across a wide range of sectors allows a whole systems approach to be taken. For example, by considering how industry, homes and

[19] Heat Networks Zoning Pilot, Gov UK (2022) https://www.gov.uk/government/publications/heat-networks-zoning-pilot

[20] Energy Bill [HL], UK Parliament (2022) https://bills.parliament.uk/bills/3311

commercial sites may share infrastructure and/or resources (e.g., waste heat). This would build the understanding of grid implications and help identify novel ways to minimise network impacts, and innovative business models. This would further reduce uncertainty, encourage planning alignment, and improve coordination.

Whilst some instruments to facilitate industrial decarbonisation will require UK Government intervention, Welsh Government should work with the above partners to create an enabling environment to attract traditional industry and/or develop new industries. This could be done for example, through clean growth hubs, which could bring together LAEPs with industry and network infrastructure. This should happen in the short-term, but periodic reviews should be undertaken to account for innovation around industry, business models and decarbonisation technologies.

Electrification could play an even larger role in industrial decarbonisation if barriers around cost of electricity and availability of these options at scale could be removed[21]. Welsh Government should work with the UK Government to remove barriers and demonstrate industry decarbonisation options which have the potential to be cost effective in the future. This could be electricity-based options but also includes hydrogen, natural gas (with CCUS) and bioenergy.

Recommendation 5: Continue to use available policies that support the deployment of renewable generation in the right place at the right time.

The modelling completed in this project suggests that offshore wind is likely to be the most cost-effective and predominant source of electricity production in a least-cost, Net Zero Welsh energy system. In the Technology-Optimistic and Societally Optimistic scenarios, offshore wind provides 23% (3TWh) and 41% (8TWh) of annual electricity supply in 2030 and 80% (72TWh) and 63% (57TWh) by 2050. However, a range of technologies are likely to be required to ensure diversity and security of supply and there are broader considerations to account for when enabling different sources of renewable generation (e.g., local benefit, community acceptability and energy planning consent). This could include other variable renewable generation such as solar, onshore wind and, potentially by 2050, tidal generation, alongside firm generation options such as hydrogen fired turbines and nuclear generation.

In the Technology-Optimistic and Societally Optimistic scenarios, non-offshore wind renewable generation provides 71% (10TWh) and 53% (10TWh) of annual electricity supply in 2030 and 17% (12TWh) and 11% (11.8TWh) by 2050. This is mainly onshore wind, with around 1TWh of solar PV in both scenarios across 2030 and 2050, a smaller amount of hydro power, and in 2050 only 2.5TWh of tidal stream generation, again in both scenarios.

Whilst offshore wind, nuclear and hydrogen generation deployment is largely within the remit of the UK Government (e.g., CfD auctions), the Welsh Government can and should provide leadership and support to ensure a diverse range of renewable technologies are present in the Welsh energy system. This could include a continuation of the positive planning landscape, and the development and ownership of renewable energy schemes, which could be facilitated through the ongoing Welsh Government plan to establish a renewable energy developer for Wales[22].

Welsh Government should also work closely with Local Authorities and developers to identify barriers (e.g., network connections; planning issues) and convene the investment and local

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[21] However, the potential impacts on peak demand would still need to be understood and if necessary mitigated.
[22] Renewable Energy Developer for Wales, Welsh Government (2023) https://www.gov.wales/renewable-energy-developer-wales

communities to stand ready to drive delivery of the renewable energy opportunities identified in LAEPs. This should happen in the short term to align with the time frames for LAEPs in Wales, which are due to be completed by next year, and the development of a renewable energy developer for Wales which is ongoing.

Recommendation 6: Set out the preferred energy system outcomes, where appropriate, to provide more clarity on the Welsh energy system transition.

Welsh Government should provide leadership and minimise uncertainty where appropriate and possible by continuing to set out its priority outcomes for the Welsh energy system (e.g., providing economic benefits to Wales; ensuring environmental sustainability; encouraging people to insulate their homes). This will help provide clarity as to how these priorities could impact the system and energy networks in the future. This is a broad recommendation which stretches across the energy system, but key areas where Welsh Government could facilitate and set out priorities include network connection routes and decarbonisation priorities:

- The routing of network connections for offshore and onshore wind is still uncertain. Whilst planning permission for transmission networks is not devolved, Welsh Government should work with network operators to inform citizens of the potential benefits, or negative impacts, network routes may bring. For example, providing more network connection opportunities for Wales or enabling an offshore wind industry that may provide skilled jobs, or adverse environmental impacts.
- Welsh Government should review and explore how top-down priorities relating to the whole Welsh energy system align with those priorities coming from the bottom-up process of Local Area Energy Plans (LAEPs), which are due to be completed next year. Welsh Government should then work with TSOs, DNOs and GDNs, LAs, business, and industry to deliver on these priorities. This process of considering priorities from a top-down and bottom-up perspective will provide a greater degree of confidence in making anticipatory investment decisions.

Recommendation 7: Actively explore and communicate the benefits of a North-South electricity transmission connection.

The route of the North-South electricity transmission link has not yet been determined. Transmission lines can be controversial and face local opposition. The Welsh Government can demonstrate leadership, act as a convening institution and help bridge the different perspectives of citizens impacted by routing options. Welsh Government should engage with NGET to convene and feed-in the views of Welsh stakeholders around potential routes during the initial stages of design.

This should include the key consideration that if an onshore route is chosen, rather than an offshore route[23], there is the potential for improved network connection opportunities in Wales (e.g., opening up the potential for connections for solar and onshore wind generation). Any negative impacts of specific routes, or types of routes, should also be considered. For example onshore routes may have a greater environmental impact (e.g., impact on visual amenity). This could support Wales to achieve its ambitions, unlocking certain decarbonisation options and

[23] "Onshore" electricity transmission lines (i.e., transmission lines not connecting offshore assets to the onshore grid) can be routed offshore to avoid some of the challenges faced from purely onshore routes.

helping Wales prosper from the transition, developing skills, and supporting economic growth and community energy.

Recommendation 8: Support the accelerated uptake of Demand Side Response (DSR) solutions.

Welsh Government should work with Local Authorities and relevant public sector bodies to support the accelerated uptake of DSR options which act as flexible energy system resources. Smarter energy systems with increased potential for DSR could open up market opportunities for people in Wales and help to support networks to reduce the impact of peak energy requirements.

The modelling for this project has provided evidence suggesting that thermal storage and smart heating, EV charging and building retrofits are likely to be the most appropriate options for a low-cost energy system, but other options such as smart devices and LEMs should also be considered. Welsh Government should work with Local Authorities to help industry bodies support the uptake of DSR solutions by developing guidance to assist their decision-making, raising awareness with the public and working with networks to develop and demonstrate DSR solutions. With significant electrification, including heating and transport, expected to occur over the next ten to fifteen years (see Recommendation 1 and Section 4), and given the lead time on installing technologies and in particular developing markets, this guidance should be developed urgently.

Recommendation 9: Assess the benefits and risks of different hydrogen production technologies, at specific locations, starting with green hydrogen.

The need for hydrogen in a cost-effective Welsh energy system is likely to ramp up, with annual Welsh hydrogen consumption in 2030 at 0.9TWh and 3TWh for Technology-Optimistic and Societally Optimistic respectively, and 10.5TWh and 9TWh in 2050 (with a further 14TWh being exported to the rest of GB in Societally Optimistic). By 2050 the role of hydrogen within Wales is similar across both scenarios with the main uses being for shipping and industrial processes. However, by 2050, the methods used to produce hydrogen and the total amounts produced (once exports are accounted for) varied across the scenarios. This can result in significantly different impacts on the energy system with electricity demand heavily impacted by levels of electrolysis deployment.

Some green hydrogen production from electrolysis was present in both baseline scenarios by 2050. However, the scale of electrolysis suggested varied considerably (from only 140GWh in Technology-Optimistic to 19TWh in Societally-Optimistic by 2050).). Additionally, the use of other technologies to produce hydrogen such as steam methane reformation (i.e., blue hydrogen) or hydrogen supported by nuclear generation also varied between scenarios. In reality, a number of local conditions and decisions, and UK Government decisions will determine whether and where these technologies are deployed. Therefore, Welsh Government should explore technology options further to understand the drivers, as well as potential benefits and risks for supporting investment decisions related to all hydrogen production technologies, at specific locations. Timeframes for this should recognise the UK target of 10GW of hydrogen production by 2030[24].

[24] British energy security strategy, UK Gov (2022) https://www.gov.uk/government/publications/british-energy-security-strategy/british-energy-security-strategy

Recommendation 10: Encourage greater use of flexibility in the energy system in Wales to more efficiently manage energy demand and supply.

Flexibility within Wales should be promoted immediately and sustained throughout the transition, as it has the potential to alleviate network constraints, provide stability services and balance supply and demand. This could include DSR (i.e., EV smart charging; smart heating supported by thermal storage), existing pumped hydro storage, and new installations of storage technologies such as batteries, liquid air energy storage, and compressed air energy storage. The flexibility GB electricity and gas networks can provide should also be utilised (e.g., utilising hydrogen storage, or other forms of storage located across GB).

Welsh Government should work with developers and providers to support flexibility and storage projects, which should include continuing to ensure a positive planning environment for projects on the distribution network, where planning is a devolved matter, and working with Local Authorities to support storage and flexibility in domestic properties (see Recommendation 8).

Recommendation 11: Work with network operators to assess the benefits of a hydrogen transmission network in Wales, accounting for key uncertainties and wider economic benefits.

The need for hydrogen in a cost-effective Welsh energy system could ramp up through the 2030s and prompt the need for a transmission network – most likely in South-West Wales and potentially in North Wales. Hydrogen transmission network infrastructure in Wales could provide benefits including supporting the use of hydrogen for decarbonisation and creating skilled job opportunities. However, there are a number of uncertainties which present risks to hydrogen infrastructure, such as the safety case, public acceptance, hydrogen's role (although hydrogen for shipping and industry are the main use cases in both baseline scenarios by 2050), and location of hydrogen demand and production centres.

Welsh Government should work with the networks and industry, building on existing analysis, to quantify the potential benefits, costs and impacts a hydrogen transmission network may bring to the Welsh economy, accounting for the key uncertainties. This will support Welsh Government in arriving at a view on hydrogen transmission networks. Whilst this analysis suggests that the role of hydrogen, and therefore the possible need for a transmission network, in the Welsh energy system really ramps up from 2035 to 2040 onwards, the long lead time on infrastructure development suggests this analysis needs to happen relatively quickly.

Recommendation 12: Explore the creation of an independent function focusing on facilitating Welsh whole system network coordination and investment decisions.

Welsh Government should explore the creation of a new function to represent Welsh aspirations for Wales in the near-term, with the required expertise around energy system and network transition. This could facilitate the coordination of LAEPs and engage with the FSO, DSOs, and GDNs in the absence of the RSP[25]. There is a gap in the current institutional and regulatory landscape to unlock local decision-making – this is something that the RSPs could eventually fill,

[25] Consultation: Future of local energy institutions and governance, Ofgem (2023) https://www.ofgem.gov.uk/publications/consultation-future-local-energy-institutions-and-governance

but they are unlikely to be operational for several years, so a well-designed function could fill an important role in the near-term, and potentially longer term for some activities.

This should be set up with a phased approach to expediate its establishment. The function should operate independently from the networks and represent Welsh aspirations and needs. Through this function, Welsh Government and Local Authorities should find opportunities to work with DNOs and GDNs, acting as a Local Authority convener and arbiter in the near-term to support the alignment and aggregation of LAEPs and provide a valuable input into network plans. This work would also allow investigation of differences where alignment is not possible. This process of alignment and aggregation should also help to provide investors with confidence to invest in the assets that LAEPs identify are required. The function could also provide an advisory role to the Welsh Government on the energy system transition landscape.

1.6. NETWORK IMPLICATIONS

Set out below are key network implications for the energy networks identified during this project. These are factors that network companies should be considering in their future network planning[26].

Network Implication 1: Increases in peak electricity demand will create a need for electricity distribution network reinforcement.

The whole system analysis using ESME, carried out in this project, suggests significant increases in peak electricity demand which will require significant electricity network reinforcement, particularly on the distribution network. To provide more clarity on the extent and location of the required reinforcement, increased certainty around the location and composition of generation and end-use demands and future peak network demands is needed. Two areas with significant uncertainty and materiality for electricity networks are how much peak heat demand will be met by electrified options; and how much hydrogen will be produced by electrolysis, which could have a large impact on peak electricity demand. The former is likely to have a more significant impact in the short term as electrified heat options and electric vehicles continue to see increased deployment, whilst the latter could begin to have an impact in the 2030s where there is potential for hydrogen production and demand to ramp up considerably.

Whilst electricity network operators have plans to reinforce in the near-term, through the RIIO-ED2 price control periods[27], Ofgem's ASTI process and long-term development statements (LTDS)[28] [29], there is still considerable uncertainty around estimates of future peak demand out to 2030 and beyond, which impacts networks' ability to deliver reinforcements. The shorter visibility on some demand loads (e.g., EVs, heat pumps) creates challenges for DNOs, but the RIIO-2 uncertainty mechanisms provide an opportunity to respond quickly, as these uncertainties reduce. Improved understanding of likely future peak demands will help to inform the requirement for network reinforcement, which will in turn contribute to enabling networks to invest ahead of need. The uncertainty mechanisms should also be utilised to tackle the current and future challenge of providing additional network connections, both for new distributed generation and additional

[26] This work has used ESC's model, ESME. This is a strategic whole system energy model that can explore whole energy system futures to identify strategic implications for the networks. To understand the ultimate impact of the strategic implications, further detailed network modelling is required.
[27] RIIO-ED2 Final Determinations, Ofgem (2022) https://www.ofgem.gov.uk/publications/riio-ed2-final-determinations
[28] Long term development, National Grid (2023) https://www.nationalgrid.co.uk/our-network/long-term-development
[29] Long Term Development Statement, SP Energy Network (2022) https://www.spenergynetworks.co.uk/userfiles/file/SPM_Long_Term_Development_Statement_Nov_2022_Summary.pdf

demand. The future price control structure, currently being consulted on by Ofgem (post RIIO-2, and beyond) should be designed to provide further means to deliver further, timely, anticipatory investment post-2030.

Network Implication 2: The electrification of heat will play an important role in Wales's heat transition, but other strategies should be explored to manage the impact of peak demand on the electricity distribution network.

Electricity networks are designed to meet peak demand, so reducing this can reduce the need for reinforcement requirements. Electrification of domestic heat and transport will be a major contributor to peak demand which will drive significant reinforcement, particularly in the distribution network. Whilst network operators should prepare for a substantial level of heat electrification, it is important to understand how other technologies and approaches can be leveraged to manage peak demand, and how a combination of these technologies may align within a local area. These options include behind-the-meter thermal storage, DSR, energy efficiency measures, behaviour changes, heat networks and the potential use of hybrid hydrogen boilers in some locations[30]. These are important options to minimise whole system costs by reducing peak demand, and the quantum of reinforcement required. DNOs should maximise the use of innovative approaches to minimise peak demand and accelerate their transition to a DSO, which will also help to optimise supply and demand at the distribution level.

Network Implication 3: Decarbonisation of industry in Wales needs coordinated planning and implementation support.

The decarbonisation choices made by large Welsh industrial demand assets will impact the Welsh energy network's transition. There is an opportunity for network companies, across vectors and transmission levels, to work with NZIW, other industry bodies, and Welsh Government to assess decarbonisation options of industry. Industrial clusters should coordinate more with networks and with Local Authorities when implementing LAEPs to make their roadmaps clear to other stakeholders.

Network Implication 4: Significant increases in renewable generation will require new electricity transmission network infrastructure.

A significant increase in renewable generation will be needed as Wales decarbonises. The analysis carried out in this project suggests that deployment of offshore wind is the lowest cost option for bulk power supply. However, if other renewable energy technologies such as onshore wind, solar PV and tidal were provided with additional support mechanisms such as improved CfDs or a more positive planning environment across all of GB, then their deployment in the future Welsh (and GB) energy system could increase.

Additional transmission network infrastructure would be needed to bring offshore electricity back onshore (or indeed to transmit electricity generated from increased deployment of onshore

[30] Energy Security Bill factsheet: Enabling the Hydrogen Village trial, UK Government (2023) https://www.gov.uk/government/publications/energy-security-bill-factsheets/energy-security-bill-factsheet-enabling-the-hydrogen-village-trial

renewables such as onshore wind or solar) and detailed planning is underway[31]. This includes the North-South transmission link (see Recommendation 7 and section 11). To enable the high deployment of offshore wind needed, or other renewable generation capacity, the delivery of new transmission network infrastructure needs to be accelerated and this will require a regulatory framework which allows strategic and anticipatory investment. This is confirmed by NGESO's HND report[32].

Network Implication 5: The continued and accelerated development of renewable energy across Wales will add to the challenges involved in ensuring stability in electricity distribution networks and balancing across the transmission network.

A large deployment of renewables, which create a supply with peaks and troughs, will increase the need to manage local operability challenges like voltage and fault level, as well as balancing across the whole electricity network. ESC's analysis using ESME suggests total renewable deployment (especially offshore wind in the Celtic Sea[33]) will continue to rise from 3GW in 2020 to 5.7GW and 6.6GW in 2030 and on to 16.1GW and 18.2GW by 2050, for Technology-Optimistic and Societally Optimistic respectively. Network operators will need to be able to plan for and access a range of market technologies including hydrogen-fired turbines, nuclear generation, DSR and batteries to meet these challenges, by procuring balancing services from storage and generation operators, as well as flexibility providers such as aggregators (see section 15).

Network Implication 6: The quantity and production methods of hydrogen could have a significant impact on electricity, natural gas and hydrogen networks in Wales.

There is uncertainty around the future scale of hydrogen production in Wales, as well as the technology that produces it. The analysis carried out in this project suggests that in one future scenario, deployment of large quantities of electrolysers between 2045 and 2050, largely to be exported to the rest of GB, could increase annual Welsh electricity demand by around 18TWh. This could have major implications for electricity network reinforcement, and the need for a hydrogen transmission network for export. However, the technological and business model deployed (e.g., hydrogen production coupled with offshore wind generation) will be a significant determinant of the type of network investment required. If blue hydrogen is produced in Wales, as it is in interim years in some scenarios, then this will create some demand for natural gas which will impact the need to retain parts of the natural gas network. Deployment of hydrogen to meet demand, largely for industry and shipping, is likely to be required in the medium- to longer-term, so network operators should understand the range of future quantities and production types of hydrogen, and adapt as the future of hydrogen becomes more certain. Network operators should also work with Welsh and UK Government to reduce future uncertainty around hydrogen.

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[31] Offshore Coordination Project - latest news and staying informed, NGESO (2023) https://www.nationalgrideso.com/future-energy/projects/offshore-coordination-project/latest-news

[32] The Pathway to 2030 Holistic Network Design, NGESO (2023) https://www.nationalgrideso.com/future-energy/pathway-2030-holistic-network-design#:~:text=The%20Pathway%20to%202030%20Holistic%20Network%20Design%20(HND)%20is%20a,it's%20needed%20across%20Great%20Britain

[33] Although for this project ESC generally assumed offshore wind in the Celtic sea connected to Wales, there may be additional capacity in the Celtic Sea connecting elsewhere, and capacity in the Irish Sea connecting to Wales. This is discussed further in section 10.2.1.

Network Implication 7: Natural gas network operators should explore the need and value for a hydrogen transmission network in Wales.

Natural gas networks owners should continue to investigate the need for, design and feasibility of a hydrogen transmission network in Wales. As noted in Network Implication 6, uncertainty exists about hydrogen production methods and hydrogen's role within Wales and the rest of the UK's future energy system. However, this project has found it could start to be cost effective for the energy system for parts of industry and use in dispatchable power generation from the early to mid-2030's. Hydrogen production is possible from a variety of sources including electrolysers, natural gas with CCUS (blue hydrogen), nuclear heat and biomass. By 2050 the most cost-effective system is likely to include green hydrogen and some combination of the other sources. Detailed local analysis will be required to plan exact routes, but the need to transport hydrogen for these purposes away from potential production centres in North Wales (e.g., Deeside, Connah's Quay or Wylfa regions) and in South Wales at Pembroke, is likely.

Large scale hydrogen storage would be required to support hydrogen turbines in South Wales, which are expected to be needed to provide flexibility, system services and to meet peak domestic electrical heat demand. Whilst large scale hydrogen storage options in Wales should continue to be considered, it is likely that geological siting requirements will mean hydrogen storage in England will be required to support demand in Wales. This would require a hydrogen transmission network linking the potential storage facilities in England to the demand in Wales. However, if cost-effective large scale hydrogen storage options can be developed in Wales, then it may be economic for a transmission network to export hydrogen from Wales to England.

Network Implication 8: Demand Side Flexibility can reduce but not remove the impact of peak demands on electricity distribution networks.

DSR options, especially smart EV charging, and smart thermal storage enabled heating, can smooth electricity demand, helping to limit the impact of peak demands in Wales. This could reduce peak demand by 400MW, ~10% by 2050, based on the modelling carried out in this project (see section 11.2). This can impact how DNOs manage peak demands and so increased understanding of levels of smart charging and heating will be important. This should account for uncertainties such as the rollout of the required technologies, consumer engagement, development of suitable business models (e.g., aggregators) and the deployment of digital infrastructure needed to facilitate efficient DSR.

DNOs should harness demand side flexibility to aid in the efficient operation of the distribution networks as well as reducing the overall reinforcement needed, therefore reducing costs. However, rapid progress on developing DSOs and the associated markets and digital infrastructure required to access flexibility already in the energy system is fundamental to achieving this, so should be prioritised and accelerated. LEMs, which aim to establish a marketplace to coordinate energy use and demand within a local area, can be one way to promote the use of demand side options. DNOs/DSOs can then buy flexibility services which the LEM provides.

Network Implication 9: Energy system planning should be carried out on a whole system basis, aligning local, regional and national network activities. Designed and implemented correctly, the Regional System Planner (RSP) could play a crucial role in the medium-term, aligning local, regional and national network activities.

Network operators already engage substantially with Welsh Government. However, understanding the full implications of complex network activity for the Welsh energy system requires specialist knowledge. A whole system approach to effectively coordinate between Welsh Government aims, local plans and network investment plans would increase the likelihood of a cost efficient and optimised Welsh energy system compared to current institutional arrangements.

The precise role of the RSP is yet to be defined (and a separate function may be required in the near term – see Recommendation 12), however, if the RSP is able to effectively coordinate between Welsh Government aims, local plans and network investment plans, this could increase the likelihood of a cost efficient and optimised Welsh energy system compared to current institutional arrangements.

Network Implication 10: All energy networks should explore how whole system network planning can minimise transition costs.

This study highlighted the interactions between different energy vectors, for example the impact of other heat sources on electrical heat demand. It also highlights the need for coordination and engagement between a range of energy stakeholders including, Welsh Government, Local Authorities, network operators, industry and Welsh citizens. This demonstrates the need for whole system network planning, where all vectors and actors are considered when planning for energy network infrastructure, to minimise transition costs. Beyond this work, the Welsh Government's own Renewable Energy Deep Dive[34] and Ofgem's recent consultations[35] all reinforce the need for whole system planning. The challenge now is making this a reality. Welsh Government is uniquely positioned to support whole system network planning through their support of LAEPs across all Local Authorities in Wales. Network operators should engage with each other, Welsh Government and Local Authorities (on LAEPs and more broadly) and wider energy stakeholders to help ensure their network plans and investment process take a whole systems approach.

Network Implication 11: There is an important and increasing role for heat networks in a Net Zero Welsh energy system.

Heat networks can provide a meaningful contribution to total future heat demand in a cost-effective future Welsh energy system, particularly in urban areas with high population density, or areas near a large heat source (e.g. a cogeneration plant fuelled by nuclear power). Analysis from this project suggests heat network deployment could accelerate through the 2030s and provide around 15% (2TWh) of annual building heat demand in Wales by 2050. This could result in an increased number of heat network operators as well as an increased requirement for the skills

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[34] Renewable energy deep dive: recommendations, Welsh Government (2021) https://www.gov.wales/renewable-energy-deep-dive-recommendations

[35] Consultation: Future of local energy institutions and governance, Ofgem (2023) https://www.ofgem.gov.uk/publications/consultation-future-local-energy-institutions-and-governance ; Consultation on frameworks for future systems and network regulation: enabling an energy system for the future, Ofgem (2023) https://www.ofgem.gov.uk/publications/consultation-frameworks-future-systems-and-network-regulation-enabling-energy-system-future

required to install and operate them. Such networks are also subject to supply and demand variations due to differing demands across the year. As with the electricity system, a heat network solution must be able to accommodate extreme cold spells. The availability of local resource – for example, whether thermal plant or heat pump – will inform the nature of the heat network solution, with heat storage and backup ("peaking") boilers likely to be required.

1.7. SUMMARY

To achieve Net Zero by 2050, many of the identified Welsh Government recommendations (section 1.5) and network implications (section 1.6) require immediate implementation or action. This is either because they are prerequisite enablers for other critical path investments, or due to long delivery times – networks are one of the most important areas where change is required. Implementing the recommendations, and recognising the impact of the network implications, from this work will be a key step towards ensuring that Wales remains on course to fulfil its Net Zero ambitions and can prosper from the transition. Building an increasingly detailed understanding of the network implications will contribute to ensuring network companies are preparing to play their part.

PART B – EVIDENCE

2. INTRODUCTION

This technical part of the report sets out the context within which this project was carried out, the approach taken, and the background analysis that led to the insights, Welsh Government Recommendations and Network Implications.

Section 2 gives an overview of the history and current situation of the gas and electricity systems in Wales, an introduction to the complexities and limitations of the processes in place to regulate future network developments, and a discussion of the approach taken in this project, including more detail on the scenarios and sensitivity scenarios used in the analysis.

In Sections 3 to 15, the individual insights emerging from the analysis are discussed. Each of these is presented along with the supporting evidence and ends in a recommendation to Welsh Government.

Section 16 then presents a set of Network Implications. These were derived from the insights and recommendations and are factors that network companies should be considering in their future network planning work.

2.1. HISTORY AND CONTEXT

The electricity and gas networks in Wales have developed over the last 100 years to satisfy the demands and complement the resources of Wales while integrating them with the wider Great British (GB) energy system. Over the coming decades, as the energy system transitions to deliver Net Zero, with different demands and resources, significant network change will need to occur, dramatically reshaping the network infrastructure landscape across Wales. The following sub-sections provide some background context for readers less familiar with the history and structure of the energy networks in Wales. Those with an existing understanding should proceed to section 2.2.

2.1.1. ELECTRICITY SYSTEM IN WALES

The GB electricity grid as we know it today has gradually evolved since the creation of a national grid system in 1925. This National Transmission System (NTS) connected large scale power plants together, as well as linking local distribution systems. The early growth of the electricity system was driven by the need to provide electricity for industrial production, as well as to improve the quality of life for domestic consumers.

As demand for energy services grew over the second half of the last century, the distribution system expanded to reach more of the population and deliver higher capacity, while more large-scale generation was connected at the transmission level. The current electricity network in Wales is shown in Figure 2. As can be seen, the North and South Wales sections of the transmission network are not directly connected to each other and demonstrate the important interaction of the Welsh energy system with that of the rest of GB.

With no transmission network in mid-Wales, a greater reliance is placed on the electricity distribution network. Some of these limitations are already manifesting as bottlenecks in distribution network capacity and long delays in gaining network connections for new generation and demand assets. This is likely to increase in the coming decades as the nature of the system changes, with more demand due to the electrification of heating and transport, and an increasing amount of generation connected at the distribution level, mainly in the form of renewables.

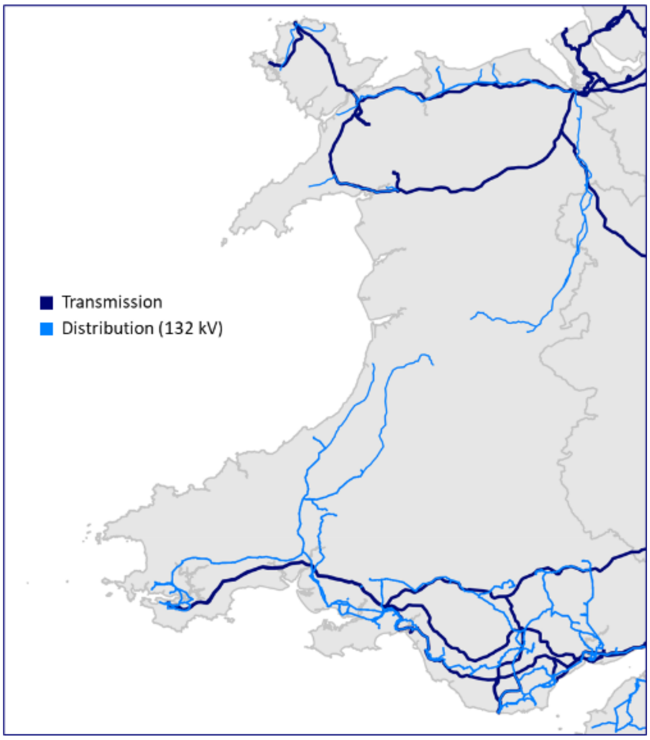

Figure 2: Current electricity network infrastructure at both transmission and 132 kV distribution levels

2.1.2. NATURAL GAS SYSTEM IN WALES

The natural gas system in Wales originates from the late 1960s, when the first pipelines were installed to connect the urban areas of Cardiff and Swansea to the growing GB natural gas transmission system. This marked a significant transition from locally produced town gas, derived from coal. Over the years, the network expanded, reaching more rural areas, and enabling households to use natural gas for heating, cooking, and industry to use it to feed processes. In the 1990s, an increasing number of natural gas-fired power stations were built in Wales, initiating a cross vector interaction between natural gas and electricity. Today, the natural gas network in Wales continues to play a vital role in meeting its energy needs.

As with the electricity transmission system, the natural gas transmission systems of North and South Wales are largely separate, as seen in Figure 3. Two NTS feeders are routed through South Wales. One connects into the rest of the NTS system and terminates in the Swansea area of South Wales. The other was completed in 2007 to connect the important natural gas import facilities at South Hook and Dragon Liquified Natural Gas (LNG) terminals in Milford Haven to the NTS. North Wales relies much more on the local transmission natural gas distribution system, with no national transmission infrastructure in place.

Across Wales, the availability of connections to the natural gas system varies by location. For example, in Ceredigion , 74% of homes are not connected to the natural gas network, whereas in Caerphilly, it is only 2%[36]. In areas without gas connections, homes are typically use oil boilers or direct electric heating.

The future of the natural gas network is uncertain as the nature of the energy system changes to meet the Net Zero target, with particular focus on the likely future extent and operations of the Gas

[36] Business, Energy and Industrial Strategy (BEIS) (2020), Sub-national estimates of properties not connected to the gas network 2015 to 2021

Distribution Network (GDN). Past studies have investigated these possibilities, including the use of biogas[37] and hydrogen, and network consolidation. However, their role in certain parts of the economy (e.g., heating) remains highly uncertain and it is anticipated that the gas network companies would need to undertake a major programme of change to support them[38] [39].

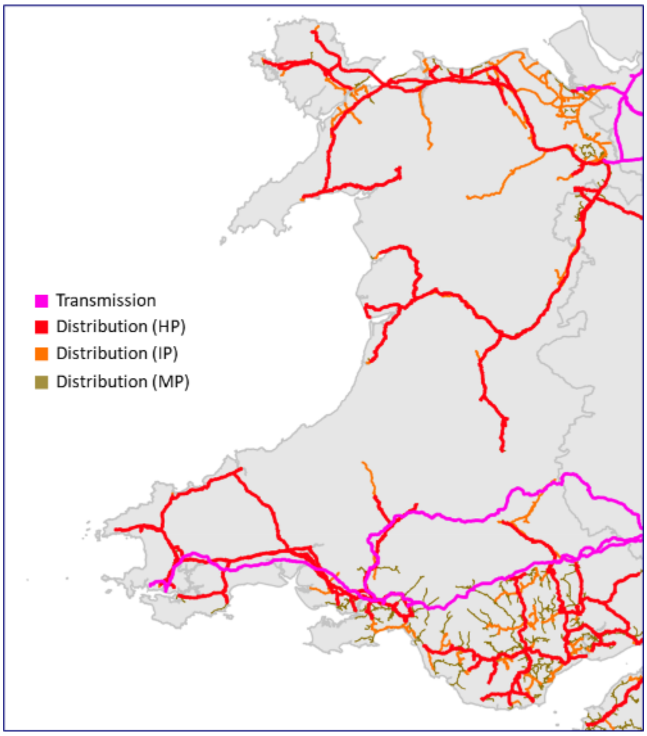

Figure 3: Current natural gas network infrastructure at transmission, and high, intermediate and medium pressure distribution levels

2.1.3. NETWORK DEVELOPMENT PROCESSES

Network investments in the GB gas and electricity systems are regulated by Office of Gas and Electricity Markets (Ofgem) to ensure value for the consumer. Ofgem agrees the funding for investment through price controls, multi-year settlements that establish the outcomes networks need to achieve and the revenues that they can receive. The network development process has undergone significant changes in recent decades and continues to evolve with the recent decisions on the RIIO-T2, RIIO-ED2 and RIIO-GD2[40] regulatory frameworks. The RIIO-T2, RIIO-ED2 and RIIO-GD2 frameworks, which cover the transmission and distribution sectors, are designed to incentivise the development of efficient, sustainable, and reliable networks. The frameworks follow a similar structure, setting revenue allowances and performance targets for each network company over a five-year price control period.

With the electrification of key sectors and changes in how electricity is generated, electricity networks are increasingly having to move from the maintenance of network assets to significant

[37] Both Technology-Optimistic and Societally Optimistic see a very small role for biogas, providing 0.1TWh by 2050 in both cases (representing 0.9% and 2.4% of total natural gas consumption by 2050)
[38] Gas Goes Green, ENA (2021) https://www.energynetworks.org/creating-tomorrows-networks/gas-goes-green
[39] WWU, Regional Decarb Pathways, ESC & Costain (2022) https://smarter.energynetworks.org/projects/NIA_WWU_2_02
[40] RIIO2 is the second iteration of the gas and electricity networks price control structure known as 'Revenue = Incentives + Innovation + Outputs' and introduced by Ofgem in 2013 for natural gas and electricity transmission networks and natural gas distribution networks. The structure was introduced for electricity distribution in 2015 (https://www.ofgem.gov.uk/energy-policy-and-regulation/policy-and-regulatory-programmes/network-price-controls-2013-2023-riio-1)

extension and increases in capacity. However, timescales for the planning, procurement, construction and commissioning of upgrades can be long and putting infrastructure in place ahead of need is a significant challenge. This can cause delays to new connections for generation and demand assets, slowing down the transition and the economic benefits that can flow from it.

One area where work is underway to address some of the challenges with infrastructure upgrades is through the work of Nick Winser in his role as the Electricity Networks Commissioner (ENC). He has been tasked by the United Kingdom (UK) Government with identifying options to reduce the time it takes to identify the need for and build onshore electricity transmission assets. Currently, this process can take between 12 and 14-years.

As noted in the Executive Summary there is a range of other initiatives going on across the sector, aimed at either directly or indirectly addressing the networks challenge, including the Future System and Networks Regulation (FSNR); the creation of the Future System Operator (FSO); the move to a centralised strategic national plan and the Accelerated Strategic Transmission Investment (ASTI) scheme.

To further promote efficiency and fairness in the charging system, Ofgem has introduced the Significant Code Review (SCR)[41] and the Targeted Charging Review (TCR)[42] as part of their ongoing efforts to reform network charging arrangements. These reforms aim to better allocate the costs of network infrastructure development and create a more transparent charging system, ultimately benefiting both network companies and consumers.

2.2. PROJECT APPROACH

The Welsh Government, conscious of the centrality of network investment to its economic and decarbonisation ambitions, aims to understand and identify ways in which it could help alleviate the challenges to reach Net Zero in Wales. To support this it appointed the Energy Systems Catapult (ESC) to deliver the Future Energy Grids for Wales (FEW) project, more details of which are in Section 1.2. Within this project, Ofgem and the energy transmission and Distribution Network Operators (DNOs) in Wales agreed to work with the Welsh Government to explore Net Zero compliant Welsh future energy system pathways to 2050. These pathways were then used to identify strategic network implications over that period.

Engaging with these key stakeholders and others (see Appendix F for a full list), ESC developed a set of whole system Net Zero scenarios to investigate a range of possible ways that the Welsh energy system could transition to meet Net Zero by 2050. This engagement ensured that a broad range of interests in Wales are at the heart of the analysis.

An initial evidence gathering phase, comprising the review of other relevant publications, and interviewing sector experts (see Appendix B) was undertaken. From this, a set of system requirements were developed to ensure the work considered all aspects of the energy system transition in Wales, including decarbonisation targets, energy security, and the need for a just transition, (see Appendix C). ESC's internationally peer reviewed Energy System Modelling Environment (ESME) whole system modelling tool was used, along with another specialist model, ESME Networks, to investigate multiple possible futures for the Welsh energy system.

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[41] Access and Forward-Looking Charges Significant Code Review: Final Decision, Ofgem (2022), https://www.ofgem.gov.uk/publications/access-and-forward-looking-charges-significant-code-review-decision-and-direction
[42] Targeted charging review: decision and impact assessment, Ofgem (2019), https://www.ofgem.gov.uk/publications/targeted-charging-review-decision-and-impact-assessment

Further details on the approach taken in delivering this project can be found in Appendix A.

2.2.1. FUTURE ENERGY SCENARIOS FOR WALES SUMMARY

For the modelling work undertaken in this project, two baseline scenarios and 42 sensitivity scenarios were used to investigate the impact of various risks and uncertainties on the future energy system. The two baseline future energy system scenarios were based on narratives centred around a 'Technology-Optimistic' future and a 'Societally Optimistic' future. Figure 4 shows a summary of the two baseline scenarios. These have taken inspiration from ESC's core Clockwork and Patchwork scenarios[43], with changes to assumptions to better represent the resources and demands of Wales, and the Welsh targets in the sixth carbon budget. The updated assumptions can be found in Appendix C.

The Technology-Optimistic scenario is built around assumptions that there is success in technological innovation, which delivers emissions abatement technologies and resources (such as biomass, enhanced carbon capture rates from CCS, and direct carbon capture). The expectation built into this scenario is that demands for energy services continue along current trends.

The assumptions surrounding the Societally Optimistic scenario are that consumer awareness and engagement leads to proactive demand reduction (e.g., slower growth in aviation, and dietary change). This scenario assumes that nature-based solutions (such as afforestation) and less technologically advanced abatement technologies combine to tackle residual emissions.

As discussed above, in addition to these two baseline scenarios, over forty sensitivity scenarios were modelled to test the robustness of findings to different assumptions. Each of these was used to investigate the impact of particular uncertainties. For example, one of the sensitivity scenarios investigated the impact on the future energy system of a reduced cost of building retrofit. A full list of the sensitivity scenarios can be found in Appendix C.

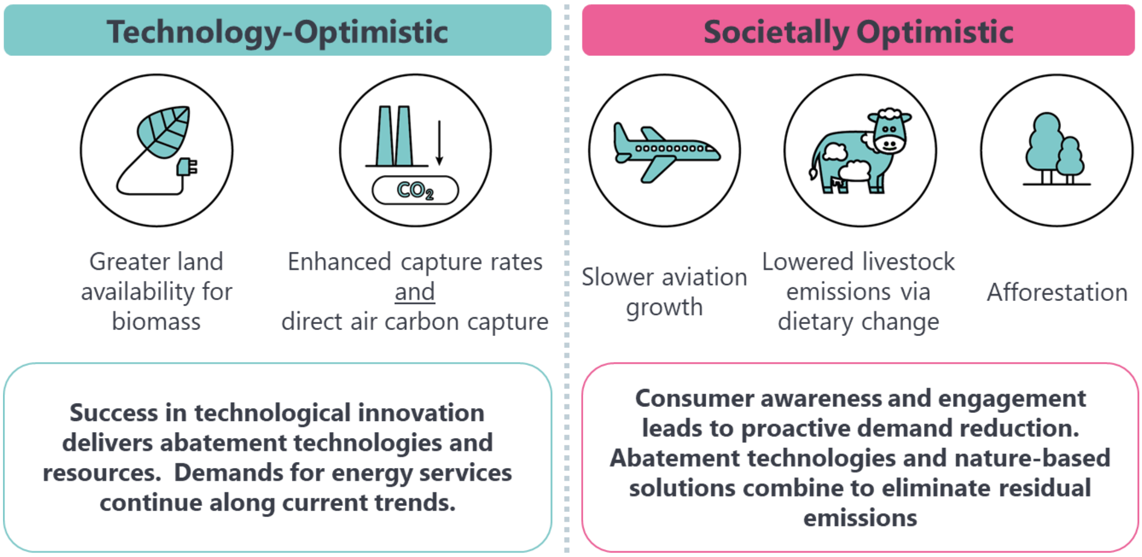

Figure 4: Summary of the Technology-Optimistic and Societally Optimistic reference scenarios

For any techno-economic modelling study, the assumptions used are critical, as these drive the optimisation process and the model outputs. The reference UK dataset associated with ESME has been curated over many years, is updated annually and has been informed by millions of pounds

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[43] Options, Choices, Actions, Energy Systems Catapult (2023). https://es.catapult.org.uk/report/options-choices-actions-how-could-the-uk-be-low-carbon-by-2050/

of ESC and, previously, Energy Technologies Institute (ETI) projects. This dataset was adopted as the starting point for analysis within the FEW project. Key assumptions were reviewed and agreed with the Welsh Government, network companies and Ofgem, ensuring confidence that the model has accounted for any characteristics that are important to them. The list of altered assumptions and a link to the full public list can be found in Appendix C.

3. KEY INSIGHTS

Drawing together the evidence provided by the evidence review, stakeholder engagement and energy systems modelling, the following sections detail the key Insights that have been developed from the modelling and broader analysis and stakeholder engagement. These are presented along with their supporting evidence and recommendations for the Welsh Government on how to move forward. A total of 12 key insights have been developed covering subjects ranging from detailed technical transition requirements to aspects of institutional design.

4. KEY INSIGHT – TOTAL ENERGY CONSUMPTION

4.1. INSIGHT

Final energy consumption in Wales could reduce by around one third by 2050 as large parts of energy demand switch from fossil fuels to low carbon electricity, driving greater efficiency.

4.1.1. SUMMARY OF ANALYSIS

Our analysis highlights the scale of change required across the Welsh energy system. To reach a cost-effective Net Zero Welsh energy system, fossil fuel consumption will need to be replaced by significant electrification alongside district heat, hydrogen and biomass for many end-uses. Liquid petroleum and natural gas consumption reduce substantially across all Net Zero compliant scenarios although fossil fuel consumption, combined with carbon capture and storage (CCS) is retained in some sectors. Compliance with Net Zero is achieved through technology and process change across all sectors, with the existing base of economic activity (i.e., energy demand from economic activity) being retained in all scenarios.

The significantly higher efficiencies of technologies such as electric vehicles (EVs) and heat pumps, relative to incumbent technologies (e.g., internal combustion engines (ICEs) and gas boilers), leads to an estimated overall reduction in final energy consumption. Where power or hydrogen production facilities are targeted to reside within Wales, this typically leads to an increased consumption of this resource in later years.

4.1.2. INFLUENCING FACTORS AND DEPENDENCIES

External factors such as global commodity prices and their dynamics will affect both the future demand for energy, and Wales's potential role in supporting the wider UK system[44]. Commodity price variations (either short-term shocks or systemic deviations from projections) may prompt energy consumers to respond through changing consumption and will affect real-world business cases for major asset projects. All modelled pathways are exposed to such global commodity uncertainties to varying degrees. How these uncertainties are resolved will influence the nature of the real-world Welsh transition pathways, with appealing characteristics of different modelled scenarios emerging, depending on the responses of individuals, business and Government.

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[44] ESC modelling uses stable (seasonally varying) commodity prices throughout the modelled period, aligned to BEIS's Fossil Fuel Projections: https://www.gov.uk/government/publications/fossil-fuel-price-assumptions-2019

4.2. EVIDENCE

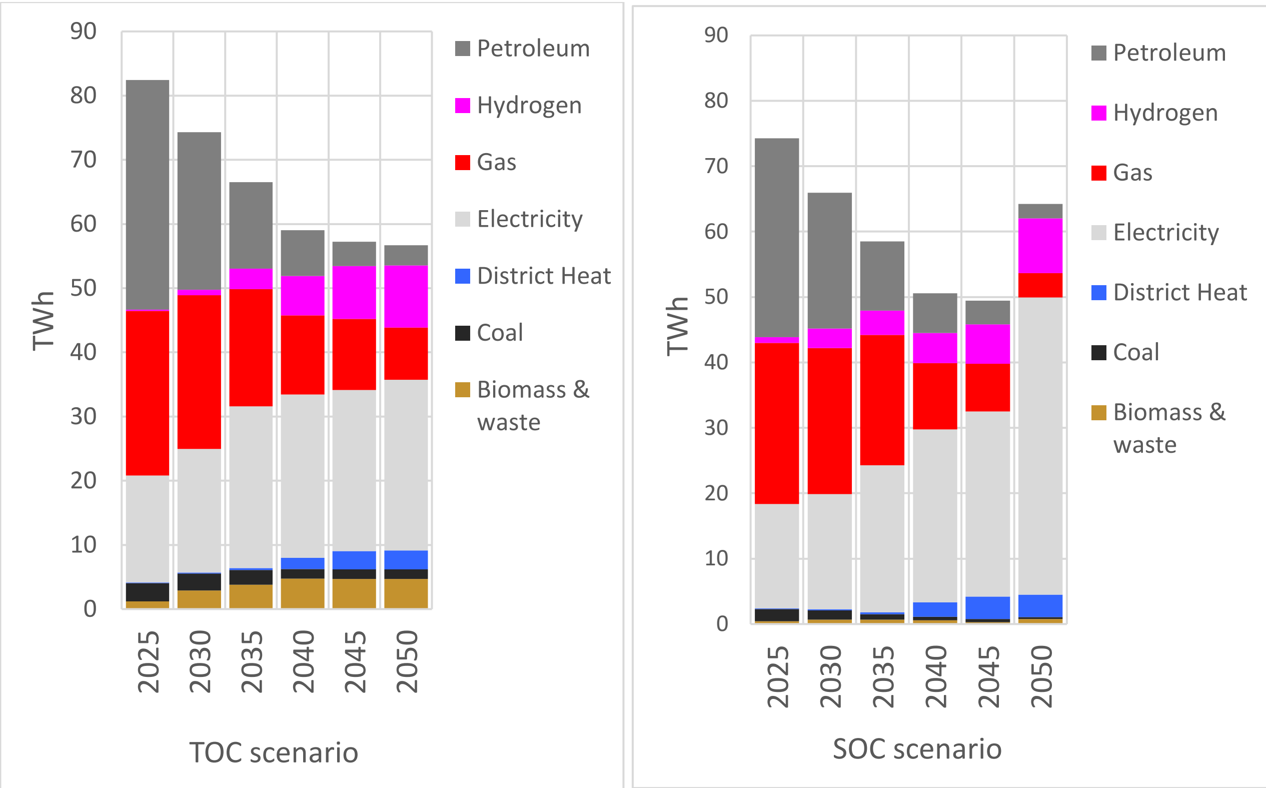

Figure 5: Annual total final energy consumption in Wales (inclusive of electricity consumption for electrolysis), 2025-2050, left: Technology-Optimistic (TOC), right: Societally Optimistic (SOC) scenarios

Figure 5 shows total energy consumption from 2025[45] to 2050 for the Technology-Optimistic and Societally Optimistic scenarios. It shows the quantity of each fuel consumed for all end-uses and includes electricity use for hydrogen production. Compared to 2025, 2050 total end-user energy demand is 30% less in Technology-Optimistic and 14% less in Societally Optimistic scenarios. There are several reasons for this demand reduction, including increased efficiency over time of newer electric-based technologies, and deployment of some building-fabric efficiency retrofits. Total energy consumption reduces less in Societally Optimistic by 2050 as there is greater electricity demand for green hydrogen production in Wales, particularly in the last five years to 2050. In the Technology-Optimistic scenario hydrogen is imported from England.

Consumption of fossil fuels falls dramatically by 2050 as a widespread shift to electricity, district heating and hydrogen takes place across the key sectors of the energy system. Petroleum use falls between 90% and 95% across the modelled scenarios by 2050, largely due to the phase-out of petrol and diesel internal combustion engine (ICE) vehicles, and gas consumption falls by 70-85%. However, fossil fuel is not wholly eliminated. The main consumers of fossil fuels in 2050 are transport and industry, with industry retaining some residual gas demand for certain processes after switches to electricity, biomass and hydrogen have been made. Energy efficiency improvements in industry help to drive down residual fossil fuel demand further and application of CCS mitigates some of the emissions associated with its combustion. In some cases, natural gas use

[45] Because of unusual changes to demand and generation in 2020 due to Covid-19, modelled trends for 2020, rather than real data were used. Tables in the executive summary have used the modelled 2020 as a starting point to provide context. However, given that we are now in 2023, charts in the main body of this report will start from 2025.

coupled with CCS is retained for blue hydrogen production, although within these scenarios, this is more extensively located outside Wales.

Electricity demand increases out to 2050 as several sectors electrify (see section 5). However, there is a range in total electricity consumption in 2050 across the scenarios due to different domestic, industrial and hydrogen-production demands. Whilst mass electrification of key sectors (e.g., transport, heating) increases the consumption of electricity, this is more than offset by the higher efficiencies of electric systems (e.g., EVs and heat pumps) which bring down total final energy consumption. Building fabric retrofits and energy-efficiency improvements in industry also help to reduce overall consumption of energy and electricity over the pathway to 2050.

Modelling indicates that district heating develops and expands from the 2030s, with both the Technology-Optimistic and Societally Optimistic scenarios showing relatively similar quantities of heat via networks, despite different end-use heat demands. The rationale for this is that heat networks offer a means of supplying low-carbon heat to buildings that are less amenable to electrification and/or areas with high-heat density. At present, heat networks are typically powered by combined heat and power plant (often fuelled by natural gas). In the future, all heat networks will be required to use, low or zero emissions heat sources to comply with interim carbon budgets.

As heat networks are likely to be developed as local infrastructure rather than transmitting hot water along lengthy pipelines, the choice of heat source will depend heavily on the resources available in the network locality and the nature of the buildings connected. Potential heat sources include large, centralised heat pumps (extracting heat from locations such as rivers or abandoned mines) and co-generation from thermal plant, potentially including nuclear power, geothermal energy, or where available, waste heat from industrial processes (the latter of these is not modelled in this study). For Wales, the choice of heat network locations and their sources of heat requires careful planning, with options for rural heat networks differing from those appropriate for urban, heat-dense regions.

A key user of energy within Wales is industry – several nationally significant industrial sites are located across the South and the North of the country. Whilst there is real world potential for industrial sites to reduce their output and energy demand (e.g., in response to purchasing trends), this may have wider economic consequences for Wales. In this modelling study, three out of the four scenarios and sensitivity scenarios (including the Technology-Optimistic scenario) that are considered in detail in relation to the industrial transition have industrial output remaining broadly consistent with the current level and composition (see section 7). Energy intensity improvements, where replacement or upgrades to industrial plant offer a means of reducing energy use without compromising product output, are included in all cases. However, the detail of such improvements will be unique to each industrial site and may be commercially sensitive.

Figure 5 also shows that a small amount of coal may be retained out to 2050 to support some heavy industry. In reality, ESC expects that national and global policies, market developments, or business choices (e.g., for steelmaking to transition away from blast furnace retention to alternatives such as direct iron reduction or to arc furnaces) will prompt an alternative fuel switching option.

4.3. RECOMMENDATION

Recommendation 1: Accelerate key enabling conditions (e.g. skills and regional supply chain) that expedite the implementation and uptake of technologies that support the changes needed to transition to a Net Zero energy system.

As the energy system transitions to meet Net Zero, there will be widespread change to the type of energy consumed. Electricity consumption will increase significantly and potentially double with the electrification of key sectors (e.g., heat and transport) – a significant amount of this occurring in the next ten to fifteen years[46]. Natural gas consumption could reduce by over 85%, largely by 2040, with residual demand coming predominantly from natural gas with CCS for industrial processes.

The scale and opportunity of the transition and the skills, investment and work required to deliver it is vast, and it must occur at pace if intermediate carbon targets are to be met. Welsh Government should continue to create the wider environment needed to facilitate this scale of change, such as skills development (e.g., engaging with training providers), citizen engagement, publication of information, enabling access to data, and the development of Welsh supply chains. Whilst the Welsh Government may not have all the direct levers within its gift to deliver the transition, it can continue to play a vital role in creating the wider enabling environment.

[46] A total of 9TWh and 7TWh of consumption electrifies between 2020 and 2035 in Technology-Optimistic and Societally Optimistic scenarios.

5. KEY INSIGHT – ELECTRICITY DEMAND TRANSITION

5.1. INSIGHT

Electricity demand will increase substantially due to the electrification of heat and transport. If favourable conditions for green hydrogen production (i.e., electrolysis) emerge in Wales, this increase will be significantly higher.

5.1.1. SUMMARY OF ANALYSIS

Wales's total electricity demand could grow from around 16TWh (2022) to between 27TWh and 46TWh, by 2050. The upper figure is mainly driven by significant demand increases, particularly in later years, from green hydrogen production via electrolysis. There are several end-use cases which could result in even higher consumption of electricity, but electrolysis has the potential to be the single largest demand by 2050.

5.1.2. INFLUENCING FACTORS AND DEPENDENCIES

Increases in electricity demand in both baseline scenarios will require network reinforcement and other interventions, particularly at the distribution level (transmission level reinforcements will also be required but are largely driven by renewable imports/exports). Given lead times on infrastructure development and increasingly constrained global supply chains, this reinforcement will need to be carried out ahead of need. The scale of anticipatory investment required should be a key driver of the next regulatory price control framework design.

The impact of hydrogen production on electricity demand will be affected by the demand for hydrogen and the method used to produce it. These in turn are impacted by factors such as the safety case for hydrogen use, public acceptance, future cost of production technologies and fuel prices, as well as any global export market. These issues are discussed further in section 14 which focuses on the future role hydrogen in Wales.

5.2. EVIDENCE

5.2.1. NATIONAL ELECTRICITY CONSUMPTION

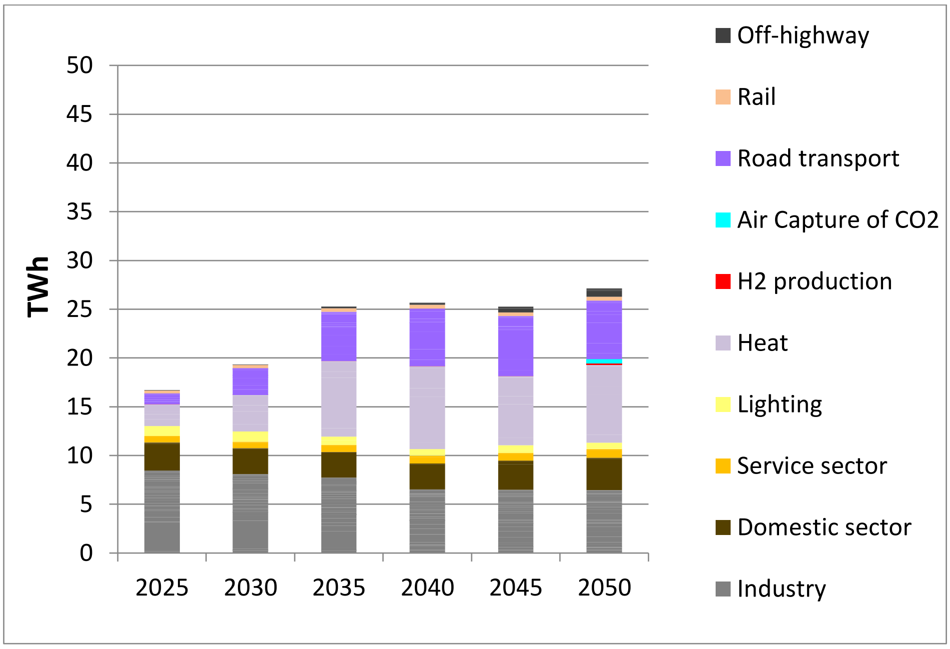

Figure 6: Annual electricity consumption to 2050 in Wales for the Technology-Optimistic (TOC) scenario

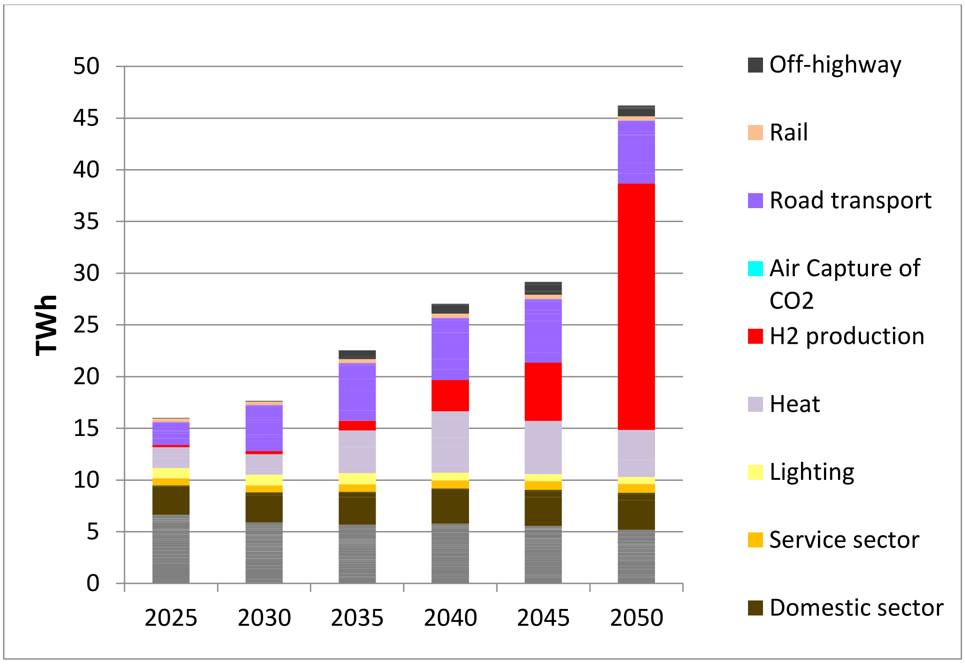

Figure 7: Annual electricity consumption to 2050 in Wales for the Societally Optimistic (SOC) scenario

Figure 6 and Figure 7 show Welsh annual electricity consumption for the Technology-Optimistic and Societally Optimistic scenarios. For Technology-Optimistic, electricity demand increases by 63% by 2050, from 17TWh to 27TWh. This is mainly due to the electrification of transport and heat, with almost all cars and vans electrifying, and electric heating (mainly air source heat pumps (ASHPs)) providing the bulk of annual heat supply (see section 6).

For Societally Optimistic, electricity demand in 2050 almost trebles. This is again partly due to the electrification of transport and heat (albeit mitigated through consumer choices leading to reduced demands for these services). For both scenarios, intermediate emission targets (e.g., carbon budgets) drive most electrification of transport and heat by 2040, with the ban on the sale of new petrol and diesel cars and vans from 2030 also impacting transport. In Societally Optimistic electricity consumption for heat demand actually reduces slightly from 2040 to 2045 as more efficient heat pumps replace some electric resistive heating (ERH).

Away from heat and transport, the scale of the increase in electricity demand in Societally Optimistic is predominantly down to a four-fold increase (from 6TWh to 24TWh) in electricity demand from hydrogen production via electrolysis, occurring in the final period, 2045-50. Whilst this represents a significant increase in electricity demand and therefore electricity generation, stakeholder engagement confirmed that other non-ESC scenarios did highlight the potential for significant demand increases over this timeframe, with hydrogen demand being a key driver.

The total electricity demand for hydrogen production of 24TWh can also be contextualised by comparing to National Grid's Future Energy Scenarios (FES) which see between 119TWh and 200TWh total electricity demand for hydrogen production by 2050 for all of GB[47]. With this study, assuming Wales has access to relatively cheap power via extensive deployment of offshore wind resource, this would help support a large demand for hydrogen production via electrolysis. In

[47] Future Energy Scenarios, National Grid ESO (2022) https://www.nationalgrideso.com/future-energy/future-energy-scenarios

Technology-Optimistic hydrogen is produced in other ways (e.g., via nuclear generation or bioenergy) and is imported from England (blue hydrogen), so does not see the same increase in electricity demand (see section 5).

In both scenarios electricity demand for industry decreases out to 2050. In Societally Optimistic this is down to some reduction in industry output, but for Technology-Optimistic it is down to increased efficiency in industrial processes in later years, not a reduction in output. This is discussed in more detail in section 7.

This demand increase in both scenarios will require huge electricity network reinforcement, particularly at the distribution level. This aligns with the RIIO-ED2 business plans of electricity DNOs such as National Grid Electricity Distribution (NGED)[48] and SP Energy Networks (SPEN)[49] which state that network reinforcement will be needed to enable these demand increases. Whilst uncertainty mechanisms in the RIIO-ED2 price control structure provide some investment flexibility, it will be important as demand increases materialise that investment occurs ahead of time.

Network reinforcement will be required under all scenarios modelled in this project. However, demand side flexibility, (e.g., from electric vehicle smart charging or smart heating, facilitated by thermal storage), which shifts electricity demand away from peak periods, can and will need to provide flexibility services to DNOs. This can allow deferral of some, but by no means all, DNO network reinforcements, while demand increases in the coming years.

5.2.2. REGIONAL ELECTRICITY CONSUMPTION

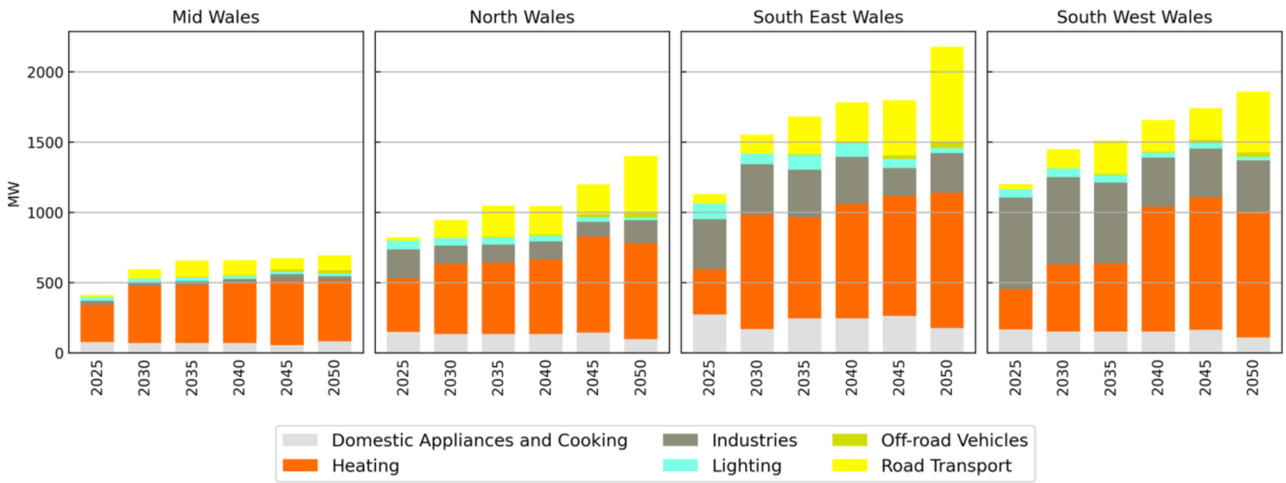

Figure 8: Regional total peak electricity demand by sector for the Technology-Optimistic scenario. The peak demands are based on absolute peak values and not peak demand time periods across the whole of Wales (i.e., each region will have a different peak demand time associated with it

Alongside the ESME modelling, the project used ESC's ESME Networks[50] model to explore how electricity demand may be distributed at a more regional scale. Figure 8 shows total maximum electricity demand, broken down by sector, for each of the Welsh regions for 2025-2050 under the

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[48] Business Plan, National Grid Electricity Distribution (2021) https://yourpowerfuture.nationalgrid.co.uk/riioed2-business-plan

[49] RIIO ED2 Business Plan, SP Energy Networks https://www.spenergynetworks.co.uk/pages/our_riio_ed2_business_plan.aspx

[50] ESC's ESME Networks model uses sub-regional data (for example Local Authority population data) to disaggregate ESME output from Wales, as a national view, into a more regional view

Technology-Optimistic scenario. It should be noted this demand may not necessarily be at traditional "peak times" but simply whenever total electricity demand is at its maximum.

Electricity peak demand increases from 2025 to 2035 as heating and road transport electrify. The greatest demands are in South-East Wales due to its larger population. South-West Wales also has a relatively large demand, in part due to its industrial demand. Industrial consumption reduces in South Wales approaching 2050 as the efficiency of electrical processes increases.

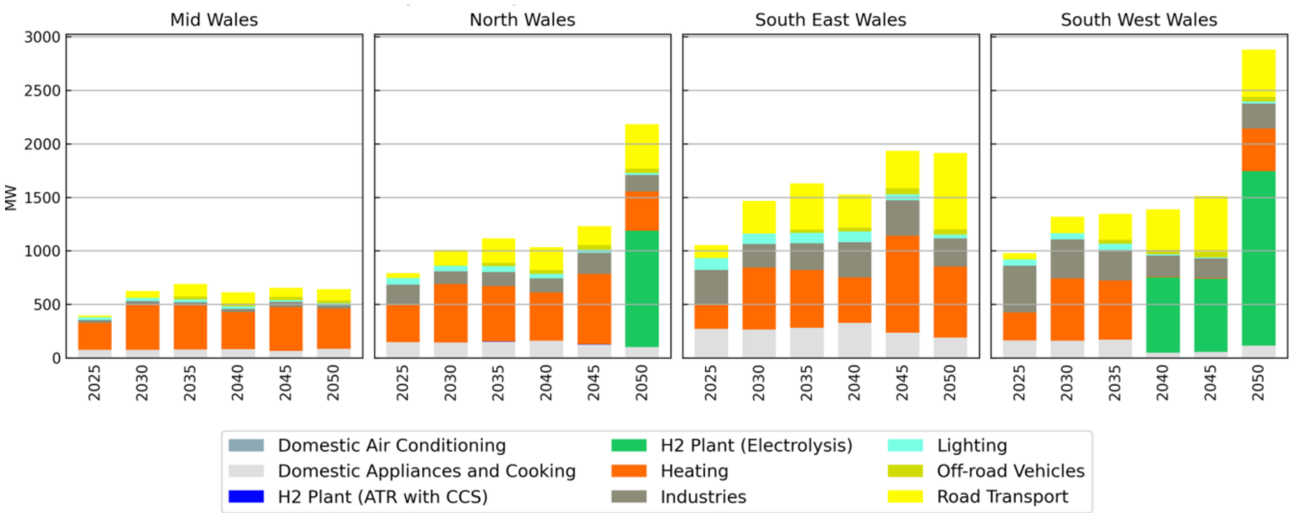

Figure 9: Regional total peak electricity demand by sector for the Societally Optimistic scenario. The peak demands are based on absolute peak values and not peak demand time periods across the whole of Wales (i.e., each region will have a different peak demand time associated with it)

Figure 9 shows total peak electricity demand, broken down by sector, for each of the Welsh regions for 2025-2050 under the Societally Optimistic Scenario.

From 2040 in South-West Wales, and 2050 in North Wales the greatest single source of electricity demand is for hydrogen production via electrolysis. For Societally Optimistic, this project found that electrolysers were selected to be sited in South-West Wales near large demands for hydrogen including Milford Haven, the South West Industrial Cluster and Pembroke Power station, if it switches to hydrogen. In North Wales electrolysers are sited near potential hydrogen turbines at Connah's Quay and Deeside. Although Figure 9 only shows peak electrical demand, the substantial increase in electricity demand for hydrogen production in 2050, particularly in North Wales, aligns with the trend in national electricity demand shown in Figure 7.

As with Technology-Optimistic, road transport and heat largely electrify out to 2035. Industrial consumption varies per region and time period but has generally reduced by 2050 compared to 2025, this is again due to efficiency improvements but also a decline in industrial output in Societally Optimistic only (see section 7).

For the Societally Optimistic scenario it can be seen that electricity demand for heating in South-West Wales appears to drop to zero in 2040 and 2045 before rising again in 2050. This is not indicating that there is no electricity for heat consumption over these periods. Rather, it is showing that the time of maximum demand for electricity is driven by when electrolysis is occurring, which for these years is overnight, when little to no heating is occurring. More generally, demand for heat is lower in Societally Optimistic than Technology-Optimistic as the former assumes greater levels of behaviour change, resulting in a reduction in heat demand whilst retaining thermal comfort.

5.2.3. LOCAL ENERGY MARKETS (LEMS)

As electricity demand grows there may be value in LEMs, implemented at a Local Authority level. A LEM is an initiative to establish a marketplace to coordinate the generation, supply, storage, transportation, and consumption of energy from decentralised energy resources (e.g., renewable energy generators, storage and demand-side response providers) within a confined geographical area[51]. Using LEMs, producers and consumers of energy can unlock value for local communities by increasing consumer participation in energy markets and supporting flexibility to shift demand.

This coordination allows energy flows to be optimised across a local network, to support flexibility and manage constraints on DNO networks. Welsh consumers could participate in such markets and save money on their energy bills. Trials have shown that someone offering their EV for vehicle-to-grid (V2G) flexibility services could save between £280-£700 a year[52]. Although other routes to market are possible, LEMs could be a highly effective one. Stakeholders highlighted the need to ensure any LEM system can provide benefits to households of all income levels. A number of projects are currently testing the LEM concept including the Liverpool Energy Xchange[53], Project Local Energy Oxfordshire (LEO)[54] and the South Cornelly LEM in Bridgend[55].

Figure 10 shows an example of what a LEM could look like.

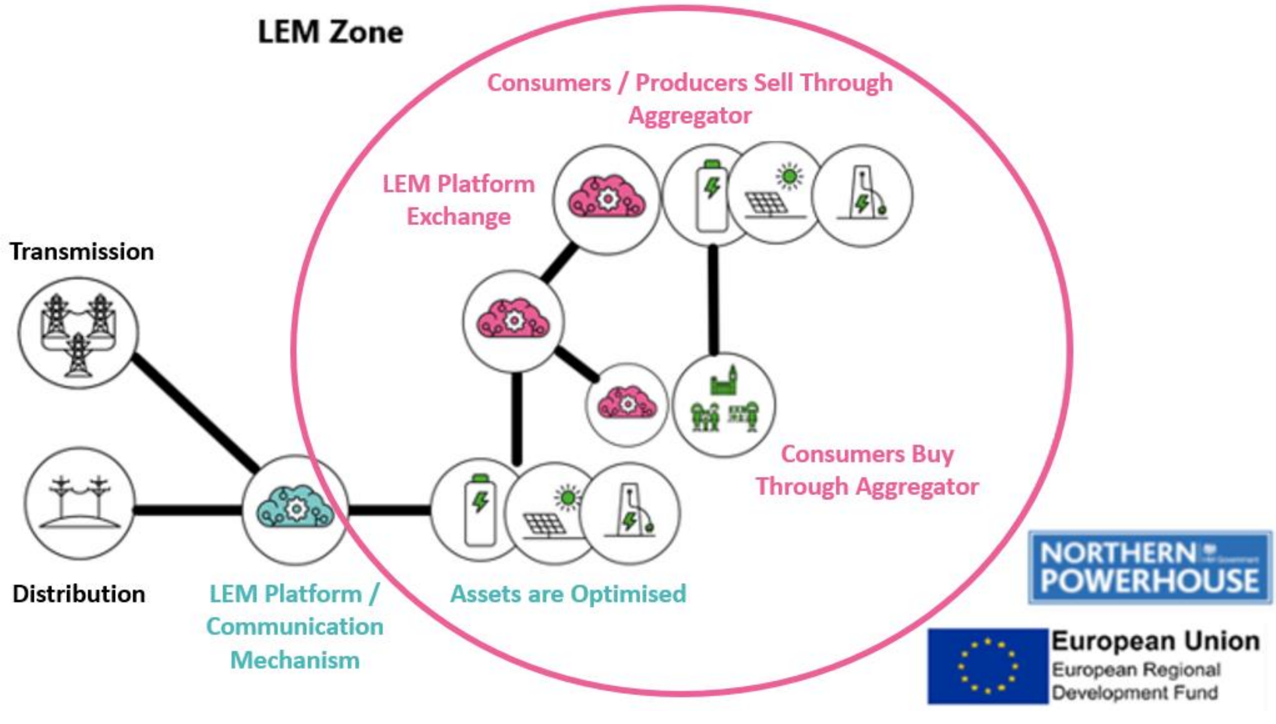

Figure 10: LEM schematic, diagram taken from the 'Unlocking Clean Energy in Greater Manchester' project

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[51] The policy and regulatory context for new Local Energy Markets, Catapult Energy Systems (2019) https://es.catapult.org.uk/report/the-policy-and-regulatory-context-for-new-local-energy-markets/
[52] 'World's largest' V2G trial finds that EV drivers could cut £725 off electricity bills, Edie Newsroom, (2021) https://www.edie.net/worlds-largest-v2g-trial-finds-that-ev-drivers-could-cut-725-off-electricity-bills/
[53] Local energy innovation for Liverpool, Liverpool Energy Exchange https://liverpoolenergyexchange.co.uk/
[54] Project LEO, Local Energy Oxfordshire https://project-leo.co.uk/
[55] South Cornelly Local Energy Market, Bridgend County Borough Council (2023) https://www.bridgend.gov.uk/residents/housing/low-carbon-communities/south-cornelly-local-energy-market/

5.3. RECOMMENDATION

Recommendation 2: Support energy networks to plan and invest for the Net Zero energy transition, particularly through the coordination of Local Area Energy Plans (LAEPs).

Peak electricity demand is the key driver of network capacity requirements. Welsh Government should work with Local Authorities and engage with network operators to ensure that LAEPs, which should be developed by next year across Wales, are coordinated at a regional level. They should also promote investment of new low-carbon technologies, whilst minimising increases in peak electricity demand. This could be through implementation of demand side interventions (see Recommendation 8), or by ensuring electrified heating options are supported by other technologies, to assist in meeting peak heat demand (see Recommendation 3).

The creation of Local Energy Markets (LEMs), which coordinate the operation of decentralised energy resources (e.g., renewable energy generators, storage and demand side intervention providers) within a confined geographical area (usually at distribution level), could help to reduce peak demands, as they incentivise a flexible and smarter local energy system. Welsh Government should build on the work of existing trials such as the South Cornelly LEM in Bridgend to understand the role of LEMs and next steps in demonstrating and scaling-up.

6. KEY INSIGHT – TRANSITION OF HEAT TO NET ZERO IN WALES

6.1. INSIGHT

Electrification will meet most annual heat demand in buildings in a Net Zero future, supported by district heat networks.

Approaches will be needed to meet peak demand and minimise network reinforcement, such as behind-the-meter thermal storage, building energy efficiency improvements, different patterns of household heat use and the potential use of hydrogen boilers in some locations.

6.1.1. SUMMARY OF ANALYSIS

The analysis carried out in this project suggests that the decarbonisation of heating in Wales will be delivered primarily through electrification and demand reduction, with most of the heat being delivered by air source heat pumps (ASHP) and Electric Resistive Heating (ERH), as shown in Figure 11. However, meeting the peak heat demand on the coldest days presents a key challenge to the electricity system. Heating systems, electricity infrastructure and a sufficient, secure supply of electricity (through suitable combinations of firm and dispatchable generation along with storage) all require significant investment.

In some situations, alternative technologies to electrification may be beneficial to help manage these peak demands. Options include in-home thermal storage (e.g., water tanks), building energy efficiency improvements, or hydrogen boilers. Hydrogen boilers may be standalone or in hybrid heating systems which include a boiler and a heat pump. Whilst hydrogen boilers can be used in a hybrid system, the boiler could be fuelled by other sources including Natural Gas or Biogas. Hybrids have the potential to be useful in reducing the heat pump size required to meet peak heat demand and therefore reduce the upfront cost, mitigating network reinforcement, and supporting buildings unsuitable for heat network connection or a non-hybrid heat pump system.

Although providing a modest contribution to total future heat demand, district heating plays a role in certain circumstances – i.e., urban areas with high population density, or areas near a large heat source (e.g., nuclear power). In these areas, homes can be supplied with hot water for space heating through a network of insulated underground pipes. Heat is supplied to the networks by one or more energy centres which provide heat from any combination of large-scale heat pumps, thermal storage, waste industrial heat, cogeneration, or heat from nuclear power stations.

The 2030s see the greatest reduction in natural gas and oil consumption for heating homes, driven by the need to meet the 6th Carbon Budget .It. is replaced by electrified and district heat. Some gas consumption is present until the 2040s and some hydrogen for heating is present from the 2030s. The phasing of any transition from natural gas to hydrogen, and the consideration of practicalities of doing so, will need to be the subject of planning work by networks, Government and Ofgem.

6.1.2. INFLUENCING FACTORS AND DEPENDENCIES

Whilst peak heat electricity demand can be challenging to meet, there are uncertainties around its exact size. This is influenced by the scale of energy efficiency retrofits, occupant behaviour and control systems, as well as the development and innovation of heating technologies that could meet this peak, especially those which have not yet been deployed at scale.

Hybrid hydrogen boiler systems are one such technology which could be useful in reducing the heat pump size required to meet peak heat demand and therefore reduce the upfront cost. However, these heating systems face a range of potential barriers to adoption (e.g., development of a hydrogen distribution network; consumer acceptance; demonstration of the safety case; supply chains; availability of a hydrogen source) and further work is required to understand the extent of their adoption and the wider network implications.

Whilst heat electrification is likely to be most cost-competitive to provide the bulk of total heat demand, network plans will need to consider possible heating futures. This includes exploring the suitability of individual technologies on a local scale; and being able to adapt as uncertainties reduce, at the local, regional, and national level. Scope for electrification of the non-domestic sector, where the building stock is of mixed heritage and solutions may vary site by site, warrants particular attention.

6.2. EVIDENCE

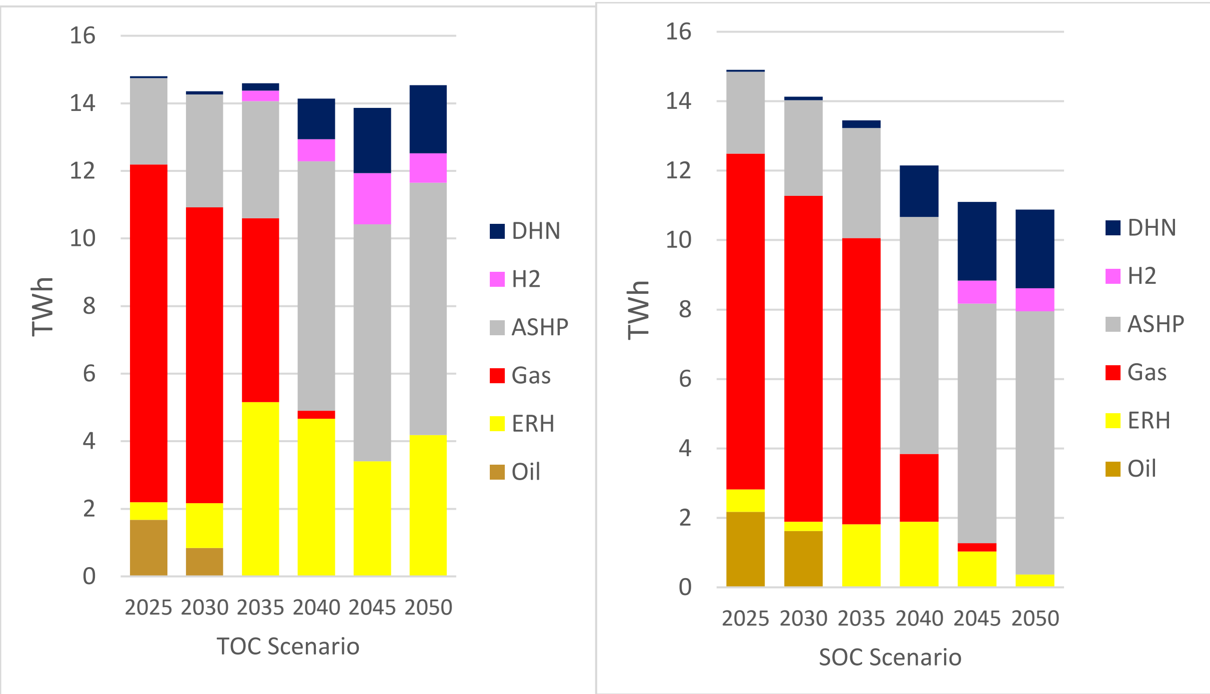

Figure 11: Annual total heat energy consumption in Wales 2025-2050, left: Technology-Optimistic (TOC), right: Societally Optimistic (SOC) scenarios

In the Technology-Optimistic scenario, population growth and thermal comfort is managed through retrofits (~ 500,000 in Wales). Conversely, in Societally Optimistic, behavioural change leads to lower demand (e.g., in response to time-of-use tariffs, or other tariffs which encourage demand reduction), whilst still being thermally comfortable, and shifted away from peak times – this, in addition to a similar insulation programme, results in a substantial demand reduction.

The heat system transition pathway differs slightly across the scenarios. Common to both scenarios are a dominant role for electrification (predominantly heat pumps) and a clear option for heat networks in high-population density areas where they are most suitable, particularly for buildings where electrification is more costly or challenging. Heat storage underpins these key options, whether at building or community scale, and allows heat demand to be spread over a greater number of hours, lowering peak demand. The analysis in this project assumes this heat storage is in the form of hot water tanks, although equally it could be one of the more innovative solutions now available (e.g., phase change material thermal storage).

With Societally Optimistic's lower demands across the energy system and slower technological change, there remains a role for natural gas for heating in Wales into the 2040s. In Technology-

Optimistic, the availability of comparatively cheap and low-emission blue hydrogen, imported from the rest of GB, helps hydrogen to be deployed sooner and meet a larger portion of heat supply than Societally Optimistic, potentially through hydrogen hybrid heating solutions.

Quantities of direct electric resistive heating (ERH,)mostly installed in buildings where an ASHP would be the primary option but the work would be expensive or impractical, vary across the scenarios. In Societally Optimistic, where total heat demand is less, the need for these technologies reduces. However, other approaches in such buildings, such as behaviour change, use of thermal storage to allow smart heating utilising lower off-peak prices, or other unmodelled interventions, may be preferred, to avoid exposure to potentially volatile electricity prices. These options warrant further exploration and subsequent guidance on advantages and disadvantages to homeowners.

6.2.1. REGIONAL ANALYSIS

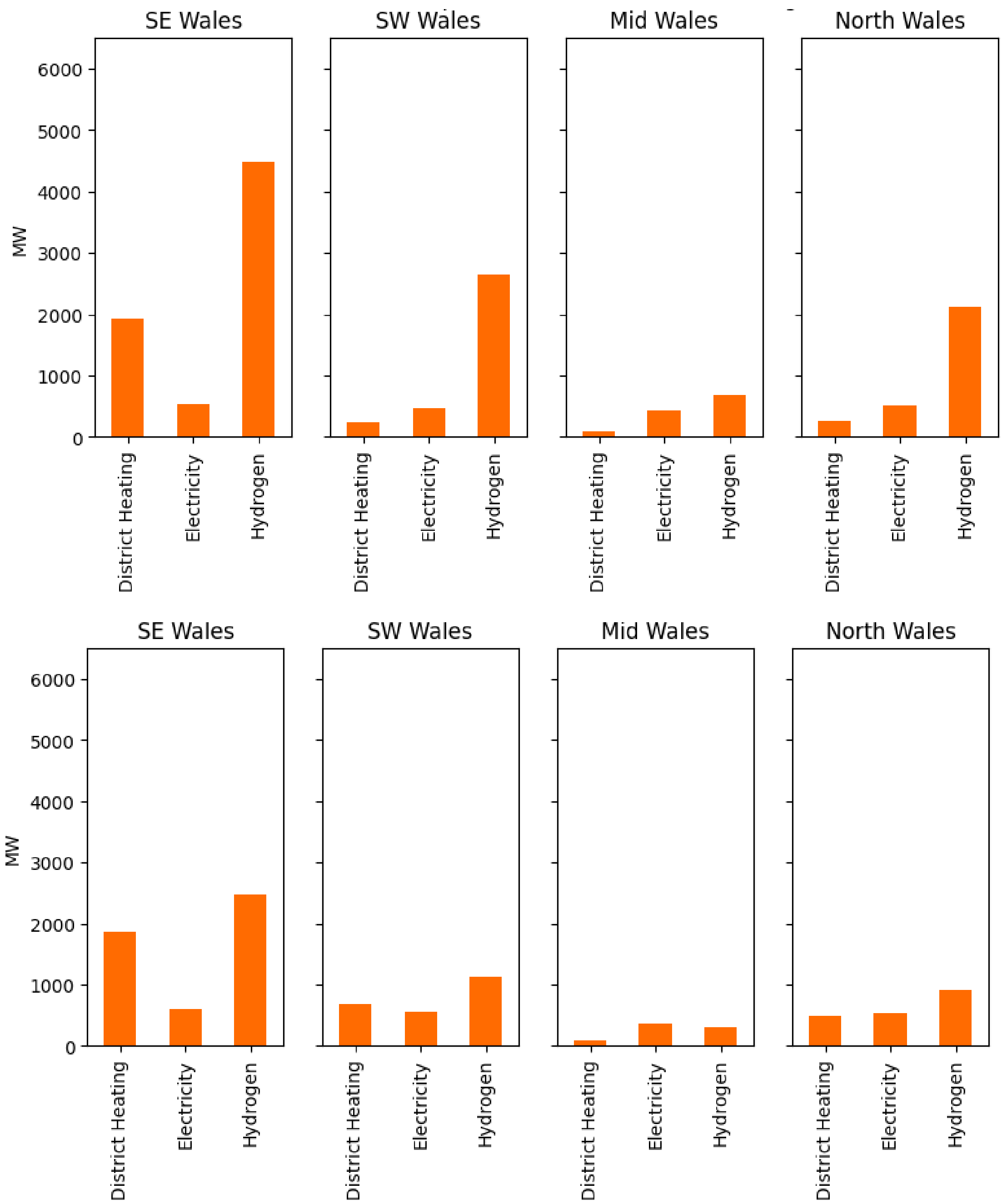

Figure 12: Peak heat consumption breakdown for each vector and sub-region of Wales for, top: Technology-Optimistic scenario and bottom: Societally Optimistic scenario

Figure 12 shows peak heat demand broken down by supply source: district heat, hydrogen and electricity heating for the Technology-Optimistic scenario (top chart) and the Societally Optimistic scenario (bottom chart) in 2050.

By 2050 hydrogen is the greatest contributor to meeting heat demand at peak times, across all regions and both scenarios (except in Mid-Wales in Societally Optimistic). This is because meeting the highest heat demands with electricity alone can be challenging in terms of the requirements on the supporting electricity infrastructure, and generation capacity to provide security of supply. Note this is only during peak demand periods. During most periods, electricity plays a much greater role in meeting heat demands, which results in the high total annual electricity consumption for heat as shown in Figure 11.

Whilst hydrogen plays the greatest role in meeting peak demand under both scenarios, it does so to a lesser extent in Societally Optimistic. This is due to the higher levels of behavioural change in Societally Optimistic which is reducing peak demand compared to that in Technology-Optimistic (see section 12). This role for hydrogen to meet peak demand, coupled with the relatively low annual total hydrogen consumption for heat, suggests that both scenarios are using hybrid hydrogen systems. However, as discussed in 6.1.2, there are also challenges to deploying hydrogen for heating including development of a hydrogen distribution network, consumer acceptance, demonstration of the safety case and the availability of a hydrogen source. More generally, there are practical, local considerations which will help decide the mix of additional heating technologies to support electrification (for example, population density/heat density of local areas, location of other hydrogen demand).

6.3. RECOMMENDATION

Recommendation 3: Support the acceleration of heat decarbonisation across Wales through electrification and other low carbon heating technologies.

The analysis carried out in this project suggests that in cost effective, decarbonised energy systems, electrification continues to increase from today, meeting as much as 8TWh (70%) of annual Welsh building heat demand by 2050. Welsh Government should support the electrification of heat through a planning policy which encourages electrified options in new buildings, and skills and supply chain development (e.g., heating engineers). In social housing, support should be given for housing decarbonisation programmes (e.g., targeted retrofit and electrification). Electrification of heat in existing buildings will be a major long-term transformation and needs acceleration in the near term in priority areas. This can be informed by Wales's LAEPs.

However, meeting all Welsh building heat demand, particularly the peak heat demand, via electrification may not be cost-effective due to generation and electricity infrastructure requirements. Welsh Government should actively engage with both electricity and gas networks to address the challenge of meeting peak heat demand, working to understand the local barriers and solutions to meeting future heat demand, and engaging with citizens to inform them of the benefits of any solution taken forward.

Welsh Government, in coordination with Local Authorities and through the implementation of LAEPs, should work to identify opportunities for alternative heating technologies. This should include heat networks, but also other technologies (e.g., thermal storage and hybrid hydrogen systems) that support electrification through the management of peak demand. Welsh Government should continue to explore the potential of heat networks in Wales and could take a similar approach to the 'heat network zoning' that is being trialled in England[56] and is currently being taken forward in the Energy Bill[57].

The outputs from this work via the LAEP process, combined with the Welsh Government's Heat Strategy, should be used to reduce network planning uncertainty by setting a vision for the future of heat in Wales. Reducing uncertainty can help create an environment where electricity and heat network companies can build the infrastructure required to support heat decarbonisation, ahead of need.

[56] Heat Networks Zoning Pilot, Gov UK (2022) https://www.gov.uk/government/publications/heat-networks-zoning-pilot
[57] Energy Bill [HL], UK Parliament (2022) https://bills.parliament.uk/bills/3311

7. KEY INSIGHT – INDUSTRIAL TRANSITION

7.1. INSIGHT

The decisions made by a small number of large industrial actors will have a significant impact on the shape of the future energy system. Continued uncertainty within large industry around decarbonisation options, is slowing the transition to Net Zero. Increased collaboration between industry, Welsh Government and other key energy stakeholders is therefore important.

7.1.1. SUMMARY OF ANALYSIS

The Welsh energy system has several large industrial demand assets. For example, just three sites are responsible for 91% of South Wales's industrial emissions – a steelworks, a cement works and an oil refinery [58]. The decisions these asset owners make on how to decarbonise is likely to have a significant influence on the shape of the future energy system, as well as the scope of economic activity in key locations in Wales. By 2050, least-cost decarbonisation options for industry could be a combination of electrification, gas with CCS, hydrogen, and bioenergy. Where green hydrogen is used for industry, this ultimately adds to electricity demand, so the increase in electrification could be present in many cases.

7.1.2. INFLUENCING FACTORS AND DEPENDENCIES

The appropriate decarbonisation solution for individual industry assets and/or sectors will be substantially influenced by preferences, business strategies and investment cycles within the industrial sector. Although some decarbonisation plans have emerged through the work of the South Wales Industrial Cluster (SWIC)[59] and other stakeholders, including in North Wales, there is still significant uncertainty in future industrial demand for different energy vectors. There is also uncertainty about how some of the key policies driven by the UK Government will support industrial decarbonisation proposals in Wales.

7.2. EVIDENCE

Figure 13 shows final industry energy consumption for Technology-Optimistic, Societally Optimistic and two sensitivities ('Increased electrification' and 'Increased H2 Availability') where a single large industry demand was assumed to switch to either electricity or hydrogen regardless of whether other options were available.

In the future, industrial energy use will switch from fossil fuels to a range of options including electrification, biomass, hydrogen, and gas with CCUS where storage is available. Total energy demand remains broadly consistent out to 2050 for Technology-Optimistic and the 'Increased H2 Availability' sensitivity scenario. It decreases for Societally Optimistic and the 'Increased Electrification' sensitivity scenario. Note that whilst Societally Optimistic assumes a reduction in industrial output, 'Increased Electrification' does not – rather it reflects the increased efficiency of using electricity for many processes.

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[58] CR Plus, 2020. ZERO2050 South Wales https://zero2050.co.uk/media/1273/wst610_southwales2050_final.pdf
[59] See https://www.swic.cymru/ for further details.

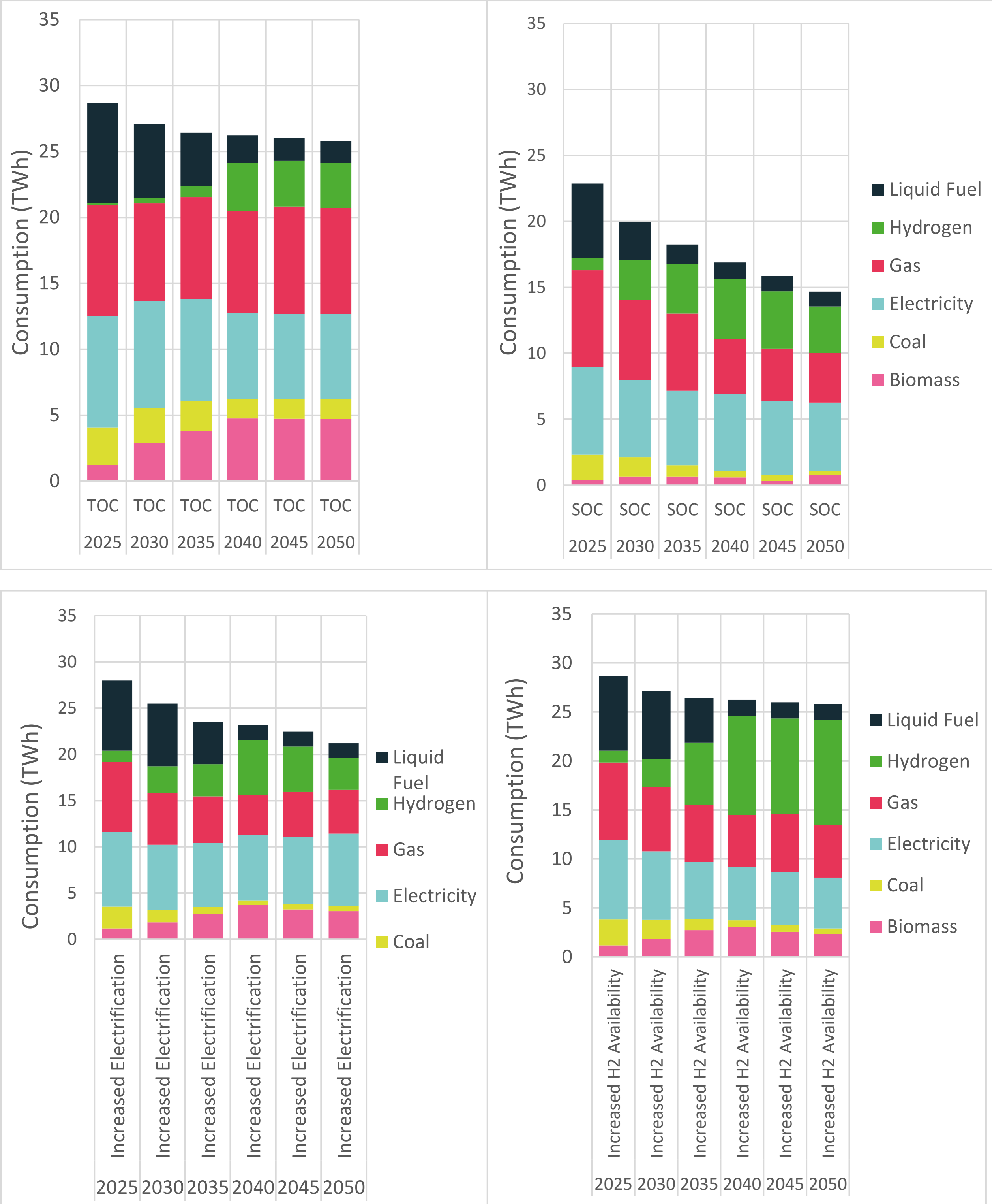


Figure 13: Total industrial energy consumption in Wales 2025-2050 for four future scenarios: top left: Technology-Optimistic (TOC), top right: Societally Optimistic (SOC), bottom left: 'Increased Electrification', bottom right: 'Increased H2 Availability'

All scenarios demonstrate a shift from unabated fossil fuel use to electricity, hydrogen, bioenergy and CCS. However, differences between the degree to which these fuel switches are made in each of the scenarios indicates there is still a good deal of uncertainty for the wider energy system and networks. Furthermore, energy efficiency improvements and/or a decline in heavy industry activity and output will also influence the overall energy requirements of industry in Wales.

In Technology-Optimistic and Societally Optimistic the spread of fuels used by 2050 highlights there is no single solution to industry demand, partly due to the different types of energy requirements across industrial sectors, but also due to uncertainty around how some of the future options will develop between now and 2050. The difference in total energy demand between these two scenarios also shows the uncertainty around how industry demand in Wales will change over the following decades.

One of the largest uncertainties regarding future industrial energy consumption is that while some plans have emerged, many industrial assets have limited information on their options to decarbonise and do not have a plan in place. Wales has a relatively small number of industrial plants with very large demand and high incumbent emissions. The decarbonised fuel switching options these plants choose will influence the whole Welsh energy system.

This is highlighted by the 'Increased electrification' and 'Increased H2 Availability' sensitivity scenarios. For these, it was assumed that a single large industrial demand asset switched to electricity or hydrogen respectively – this was not a techno-economic modelling decision, but one "forced" into ESME to explore the impact this change had on the energy system. In the case of 'Increased H2 Availability' this leads to almost half of Welsh industry energy consumption being met by hydrogen.

For 'Increased Electrification', the increase in electricity consumption is much smaller than that for hydrogen consumption in 'Increased H2 Availability', due to the increased efficiencies of using electricity. Nevertheless, as a percentage of total industrial consumption, electricity is the dominant energy source in this sensitivity scenario, meeting almost 40% of total industrial energy demand.

Between them, these two sensitivities highlight how the choices of a small number of large industrial users can have a large impact on the total industrial energy consumption and the wider Welsh energy system. This shows the need for more certainty around the decarbonisation plans of large industrial demand assets, which may in turn help smaller industrial assets take decisions, especially if located near large industry.

While the 'Increased Electrification' sensitivity focused on one industry demand asset switching to electricity, there is potential for a larger number of industry demand assets to electrify. However, this is not modelled as it is likely to be expensive when considering the need to deliver electricity at winter peak demand periods, especially since electricity is difficult to store seasonally. There are other barriers to electricity-based options such as cost of electricity compared to other fuels and lack of availability at scale of these options. If innovation and support reduces these issues, additional electrification could be more prevalent.

Alongside ESME modelling, stakeholder engagement supports many of these insights. Key points from stakeholders included:

- The Welsh energy system is influenced by a number of large demand (Industry) and supply assets. The decarbonisation pathways of these assets are likely to influence the Welsh energy system.
- There is a need for clarity on the likely route to Net Zero from many industrial consumers.
- The transition of sites to low-carbon energy consumption will take time and is unlikely to end with a single vector feeding into all processes.
- In some instances, hydrogen could be selected for industry, although this is dependent on a number of uncertainties including location.

7.3. RECOMMENDATION

Recommendation 4: Welsh Government should work with industry to identify, develop and target industrial decarbonisation options, and support the creation of an enabling environment for change.

Welsh Government, electricity and natural gas networks, and heat network providers should continue to work with Net Zero Industry Wales (NZIW) and other industry representatives to assess identified decarbonisation options for industry and identify key industrial decarbonisation drivers. Ensuring this engagement process is open to all stakeholders across a wide range of sectors allows a whole systems approach to be taken. For example, by considering how industry, homes and commercial sites may share infrastructure and/or resources such as waste heat. This would build the understanding of grid implications and help identify novel ways to minimise network impact, and develop innovative business models. This would further reduce uncertainty, encourage planning alignment, and improve coordination.

Whilst some instruments to facilitate industrial decarbonisation will require UK Government intervention, Welsh Government should work with the above partners to create an enabling environment to attract traditional industry and/or develop new industries. This could be done for example, through clean growth hubs, which could bring together LAEPs with industry and network infrastructure. This should happen in the short-term, but periodic reviews should be undertaken to account for innovation around industry, business models and decarbonisation technologies.

Electrification could play an even larger role in industrial decarbonisation if barriers around cost of electricity and availability of these options at scale could be removed[60]. Welsh Government should work with the UK Government to remove barriers and demonstrate industry decarbonisation options which have the potential to be cost effective in the future. These could be electricity-based options but also includes hydrogen, natural gas (with CCUS) and bioenergy.

[60] However, the potential impacts on peak demand would still need to be understood and if necessary mitigated.

8. KEY INSIGHT – POWER GENERATION TRANSITION

8.1. INSIGHT

A substantial offshore wind sector can form the basis of a cost-effective solution to decarbonising electricity generation in Wales.

A mix of firm and flexible power generation options (e.g., nuclear generation and hydrogen-fired turbines) are also needed to ensure a secure and least-cost energy system.

Increased deployment of renewable energy brings network planning and operation challenges that will require active, sustained and engaged collaboration to overcome.

8.1.1. SUMMARY OF ANALYSIS

Renewables play a vital role in decarbonising the UK and Wales. The mix of technologies to achieve this goal varies across the scenarios. In a least-cost, Net Zero Welsh energy system, it is likely that wind generation will be the predominant electricity source in Wales. By 2040, whilst there is around 3GW of onshore wind, wind generation is located mainly offshore (potentially between 10-13GW deployed by 2050 across the Celtic Sea[61]), as this is assumed to be the cheapest source of low-carbon electricity generation. Other renewables can help diversify supply, for example solar, tidal or wave energy may be available when wind generation is low.

High levels of offshore wind and other renewables on the network will mean system stability will need to be carefully managed. Technology options such as hydrogen-fired turbines and nuclear power can help to alleviate stability issues. Hydrogen-fired turbines are used as a dispatchable source of generation, while nuclear generation can provide firm power with some level of flexibility. This reduces but does not remove the need to import dispatchable energy from the rest of GB. Gas CCS for power generation is assumed in this analysis not to be deployed as CCS still results in some carbon emissions, so must be used sparingly. Its use is prioritised for some industrial processes where other low carbon options are limited.

8.1.2. INFLUENCING FACTORS AND DEPENDENCIES

Renewables play a vital role in decarbonising the UK and Wales with the analysis in this project suggesting that offshore wind as the predominant generating technology results in the most cost-effective system. In reality a number of factors will influence this. For example, additional support to other renewable technologies (e.g., Contracts for Difference (CfD), reformed CfDs, technology specific targets) could make them more attractive, while individual business cases may also favour specific technologies.

Nuclear power could play a role in Wales meeting Net Zero, but the technology-type (i.e., large-scale or Small Modular Reactors (SMRs)) and role could differ. Nuclear power can provide cogeneration, offering the potential to energise heat networks or flexibly manufacture hydrogen, as well as generating power. Flexible nuclear plant, able to switch between these different energy carriers could provide more value to the energy system than non-flexible nuclear plant.

[61] There may be additional capacity in the Celtic Sea connecting elsewhere, and capacity in the Irish Sea connecting to Wales. This is discussed further in section 10.2.1.

8.2. EVIDENCE

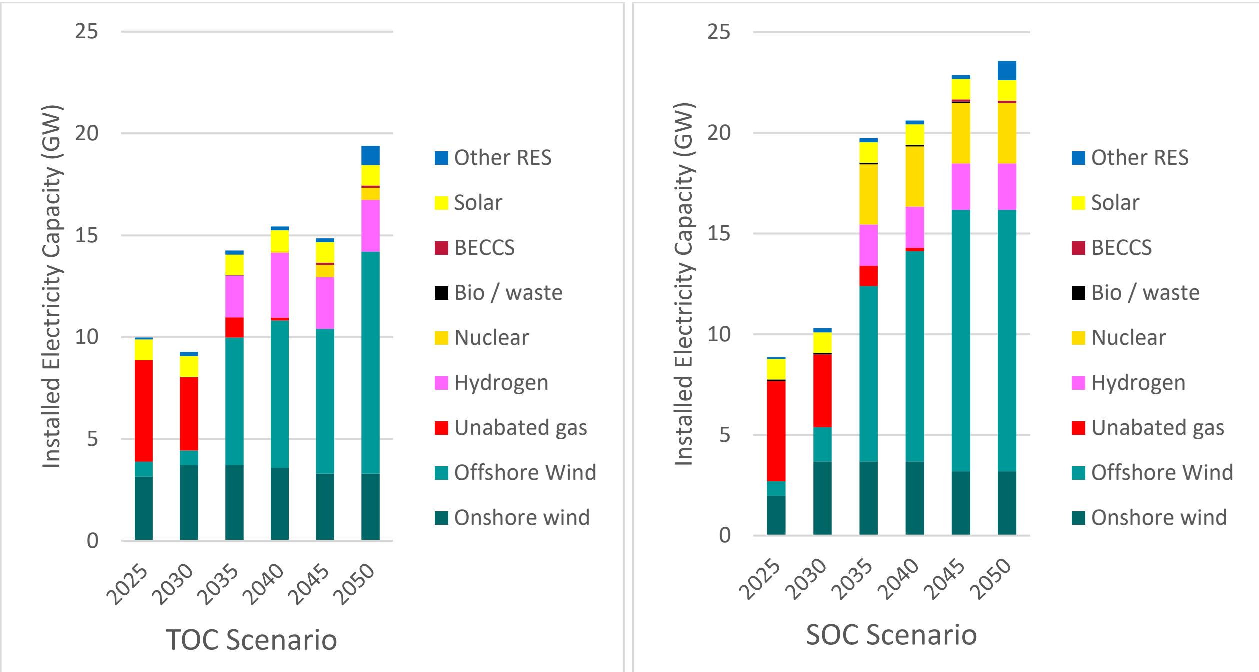


Figure 14: Installed electricity generation capacity in Wales 2020-2050, left: Technology-Optimistic (TOC), right: Societally Optimistic (SOC) scenarios

Figure 14 shows installed electricity generation capacity by technology out to 2050 for both Technology-Optimistic and Societally Optimistic. Both baseline scenarios see extensive offshore wind resource in Wales (up to 13GW by 2050), which could be located in the Irish and Celtic seas and connect to Wales. In the long term, offshore wind is favoured over onshore wind and solar, although some existing onshore wind and solar plants are assumed to repower This is because at this point offshore wind is assumed to be cheaper than onshore wind and, unlike solar, can help meet winter peak demands to a degree.

Although offshore wind is the predominant source by 2050, other renewable technologies are deployed and can help diversify supply. For example, solar, tidal or wave energy may be available when wind generation is low. The ‘Other RES’ in Figure 14 largely refers to run-of-river hydro plants and tidal stream, with tidal stream potentially playing a small role by 2050 as the technology develops.

Thermal plant capacity is retained in both scenarios with gas fired turbines being replaced by hydrogen-powered turbines by 2040. These plants run flexibly but relatively sparingly, providing power at times of low wind generation and high demand.

There is some nuclear power in both scenarios, with more in Societally Optimistic (3GW by 2050 compared to 0.6GW in Technology-Optimistic). In Technology-Optimistic nuclear generation is sized “optimally”, broadly aligned to the needs of the Welsh energy system, with a combination of light water Small Modular Reactors (SMRs) and an advanced modular Generation IV nuclear reactor[62]. Alongside producing power, Generation IV nuclear generation can provide cogenerated

[62] This is a more modern variant of the typical nuclear plants seen in GB today, often referred to as an Advanced Modular Reactor (AMR). See https://www.gov.uk/government/publications/advanced-modular-reactor-amr-research-development-and-demonstration-programme

hydrogen whilst SMRs provide cogenerated heat which powers some district heating. Being smaller in nature, such modular plant can be located closer to heat and hydrogen demands.

In the Societally Optimistic scenario, additional nuclear generation is deployed. This supports electricity demands to a significant extent in the rest of the GB system, not just that of Wales. All nuclear generation provides electricity only: without the technical innovation that underpins Technology-Optimistic, Generation IV nuclear plant and cogeneration technology innovation is slower in this scenario.

Across both scenarios it is likely that some nuclear generation would be deployed at sites with existing or historic plant capacity. However, in Societally Optimistic this approach is part of a specific strategy for nuclear across all of GB, which assumes local communities promote and accept nuclear plant where they have been located before. In practice this may mean that multiple SMRs are deployed at Wylfa and essentially act as a single large nuclear station.

There is no electricity generation with CCS in these scenarios. If deployed, it is assumed that power CCS technologies may capture no more than 95% of related CO_2 emissions. The residual emissions, although small, challenge the use of CCS in the electricity system as carbon budgets tighten. For electricity generation there are other low carbon options available, some of which are flexible and/or firm (e.g., hydrogen-powered turbines and nuclear power respectively) and so these are typically prioritised. However, CCS is used in industry where other options are more limited, and in some cases for hydrogen production as other options may have barriers. For example there is a finite resource of sustainable biomass to produce hydrogen and electrolysers can lead to additional electricity generation and infrastructure requirements (see sections 7 and 12 respectively).

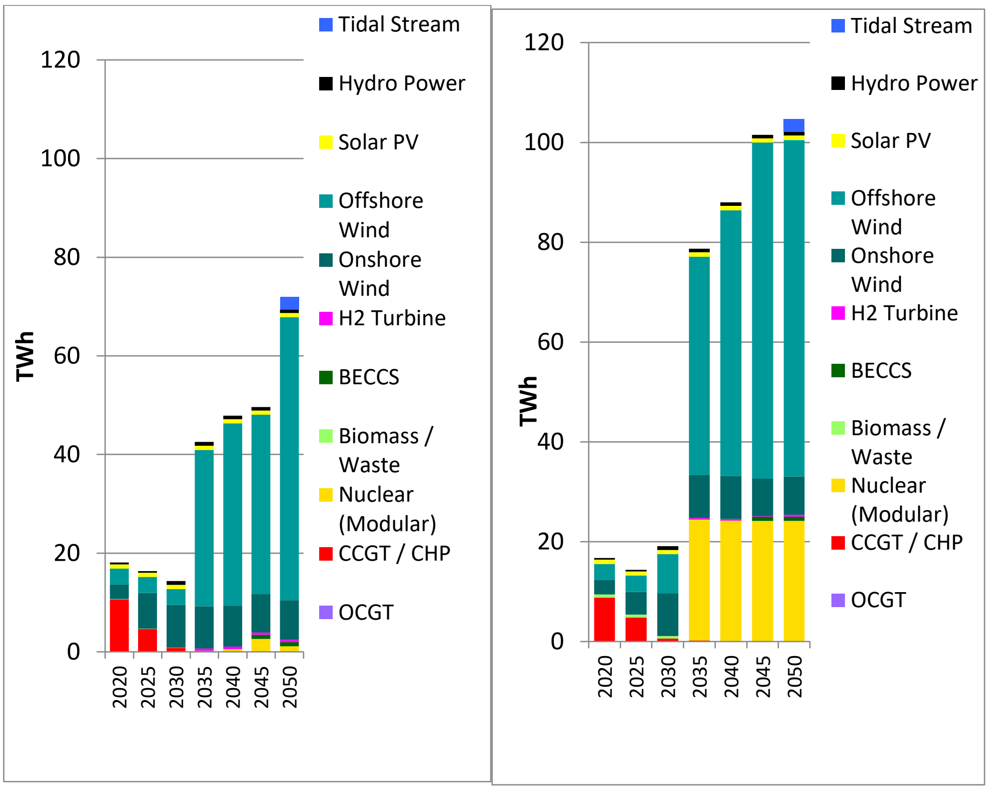


Figure 15: Annual electricity generation by technology, left: Technology-Optimistic scenario, right: Societally Optimistic scenario

Figure 15 shows annual electricity generation by technology out to 2050 for the Technology-Optimistic and Societally Optimistic scenarios. Annual electricity generation in Societally Optimistic is higher than Technology-Optimistic. This is because hydrogen is produced via electrolysis which requires significant electricity because nuclear generation is sized for GB needs not just Wales.

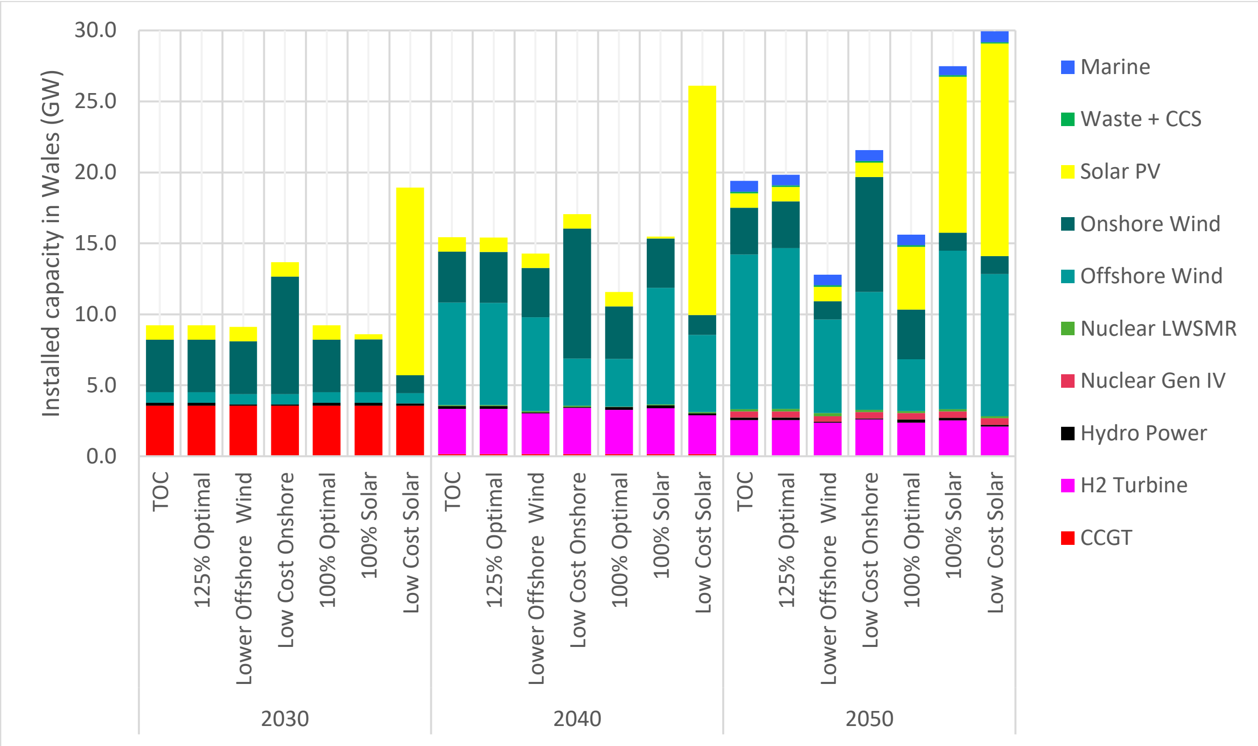
Comparing the total generation in these scenarios with total electricity consumption (see section 5) shows that Wales is currently a net exporter of electricity. It may become a net importer in intermediate years as a combination of increased electrification and reduction in gas-fired power generation outpaces the uptake of low carbon generation, before returning to net exports from 2035 in Technology-Optimistic and 2030 onwards for Societally Optimistic. Although Wales is a net exporter of electricity in the majority of future periods, in the scenarios modelled, there are still times in the year where it is reliant on imports from England (see section 9.2.1).

The Holistic Network Design (HND) produced by National Grid Electricity Systems Operator (NGESO) recommends that both North and South Wales transmission networks are reinforced to increase capacity to support offshore wind development. The Centralised Strategic Network Plan (CSNP)[63] in the future will identify if further reinforcements will be required to support future generation connections. For more information on this project findings around potential network reinforcements, see sections 9 and 10.

Stakeholders including NGESO highlighted that a reduction in gas-fired generation and increase in renewable generation can present operational challenges to the system. This includes an increased need for operational support, such as balancing of the system and ancillary services (e.g., voltage control). Meeting these challenges will require increased dispatchable plant, energy storage (section 14) and demand side response (DSR) (section 12). Hydrogen powered turbines and nuclear SMRs which are deployed in ESC modelling could play an increasing role in this area.

[63] Network Planning Review (NPR), NGESO https://www.nationalgrideso.com/future-energy/projects/network-planning-review-npr

8.2.1. POWER GENERATION SENSITIVITIES



Scenario Key:

TOC –	*Technology-Optimistic scenario (reference),*
125% Optimal -	*Case where RE originating in Wales is 1.25 x energy consumed, high OSW resource*
Lower Offshore Wind –	*Case with less offshore OSW resource assumed to be accessible*
Low Cost Onshore –	*Case with low hurdle rate onshore wind and unconstrained resource*
100% Optimal –	*RE originating in Wales is at least equal to energy consumed, low OSW resource*
100% Solar –	*Case with forced high quantities of solar power*
Low Cost Solar –	*Solar power in Wales with low hurdle rate*

Figure 16: Installed capacity of electricity generation technologies in Wales for the Technology-Optimistic scenario and example sensitivity scenarios.

Alongside the analysis of the baseline scenarios in Figure 15, this project also analysed sensitivity scenarios to explore how different assumptions for generation technologies, may impact the mix of power generation technologies in Wales. Figure 16 shows installed electricity capacity for Technology-Optimistic as a reference point and a number of sensitivity scenarios (described in the scenario key) representing a range of future worlds.

For most of the sensitivity scenarios, offshore wind remains the predominant generation technology in 2050. However, the degree to which this occurs varies. As the lowest cost zero-emission electricity source, the pathway transitions prefer this to other options.

Opting for a large Severn Barrage or a high capacity of solar photovoltaic (PV), in most cases, appears sub-optimal when considering just the energy system (i.e., omitting wider potential benefits). If included directly or through an objective of substantial "net export" of energy from Wales, these options increase the overall energy-related system costs by 2050.

If offshore wind resource proves inaccessible, Wales will need to explore other options such as solar energy, especially if a strategy of electricity export is pursued. If solar energy is provided with extra support such as policy incentives and / or new business models, which act to de-risk and prompt investment (as assumed in the sensitivity 'Low Cost Solar') then its level of deployment can be increased significantly[64].

The different scenarios modelled suggest different levels of offshore wind, onshore wind and solar. Each of these is likely to have different network requirements. For example, offshore wind will require connection along the coast and at the edges of the network. Solar and onshore wind locations are harder to determine and will be prioritised towards locations having attractive business cases. NGESO sets out the network reinforcement required for offshore wind in its HND report. For more information on potential network reinforcements, see sections 9 and 10.

8.3. RECOMMENDATION

Recommendation 5: Continue to use available policies that support the deployment of renewable generation in the right place at the right time.

The modelling completed in this project suggests that offshore wind is likely to be the most cost-effective and predominant source of electricity production in a least-cost, Net Zero Welsh energy system. In the Technology-Optimistic and Societally Optimistic scenarios, offshore wind provides 23% (3TWh) and 41% (8TWh) of annual electricity supply in 2030 and 80% (72TWh) and 63% (57TWh) by 2050. However, a range of technologies are likely to be required to ensure diversity and security of supply and there are broader considerations to account for when enabling different sources of renewable generation (e.g., local benefit, community acceptability and energy planning consent). This could include other variable renewable generation such as solar, onshore wind and, potentially by 2050, tidal generation, alongside firm generation options such as hydrogen fired turbines and nuclear generation.

In the Technology-Optimistic and Societally Optimistic scenarios, non-offshore wind renewable generation provides 71% (10TWh) and 53% (10TWh) of annual electricity supply in 2030 and 17% (12TWh) and 11% (11.8TWh) by 2050. This is mainly onshore wind, with around 1TWh of solar PV in both scenarios across 2030 and 2050, a smaller amount of hydro power, and in 2050 only 2.5TWh of tidal stream generation, again in both scenarios.

Whilst offshore wind, nuclear and hydrogen generation deployment is largely within the remit of the UK Government (e.g., CfD auctions), the Welsh Government can and should provide leadership and support to ensure a diverse range of renewable technologies are present in the Welsh energy system. This could include a continuation of the positive planning landscape, and the development and ownership of renewable energy schemes, which could be facilitated through the ongoing Welsh Government plan to establish a renewable energy developer for Wales[65].

Welsh Government should also work closely with Local Authorities and developers to identify barriers (e.g., network connections; planning issues) and convene the investment and local communities to stand ready to drive delivery of the renewable energy opportunities identified in LAEPs. This should happen in the short term to align with the time frames for LAEPs in Wales, which are due to be completed by next year, and the development of a renewable energy developer for Wales which is ongoing.

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[64] The sensitivity scenario 'Low Cost Solar' see's higher Solar PV deployment than in Technology-Optimistic because a lower hurdle rate for Solar PV is assumed which relates to extra support for this technology such as policy incentives and new business models. For the sensitivity "100% Solar", this is not the case, rather Solar PV is forced into the model to test how high levels of solar impact the requirement for other generation technologies.
[65] Renewable Energy Developer for Wales, Welsh Government (2023) https://www.gov.wales/renewable-energy-developer-wales

9. KEY INSIGHT – THE NETWORK REQUIREMENTS OF FOLLOWING PARTICULAR TRANSITION PATHWAYS IN WALES

9.1. INSIGHT

Energy networks across Wales will require significant investment to meet Net Zero.

Electricity networks will need to be reinforced to meet an increasing volume of generation and demand associated with achieving Net Zero.

Heat networks will have an important role to play in decarbonising the Welsh energy system.

Gas networks will require a mixture of redesign, recommissioning and decommissioning to manage a changing demand and transition from natural gas to hydrogen.

9.1.1. SUMMARY OF ANALYSIS

The number of generator connections increases across Wales in all scenarios modelled. Challenges may need to be overcome to incorporate the quantities of wind generation envisioned in both the North and South. The HND has recommended reinforcements for both North and South Wales by 2030. Other approaches may also be needed, including but not limited to:

- Dynamic Line Ratings
- Demand Side Response (DSR)
- Increased system flexibility
- Adoption of innovative power system technologies such as Smart Wires

Specific locations and the extent of the electricity network reinforcement required depend on technology preferences, particularly for heating and industry. Although heat pumps and resistive heating will play a key role, network preparedness for multiple solutions will be required.

Away from the electricity network, natural gas consumption will reduce significantly by 2050 but some industrial processes and potentially hydrogen production may require natural gas, alongside CCS, suggesting some form of gas transmission network will still be required.

In a future Welsh energy system hydrogen can support sectors with limited low-carbon options such as shipping, some industrial uses and to provide low-carbon dispatchable power. There is also the possibility that it will meet some building heat demand, to manage the issue of peak heat demand on the electricity network. These uses and the possibility of needing to store hydrogen in geological facilities, likely to be in England, will mean a hydrogen transmission network is likely to be required (see section 14), and in the case of heating a distribution network.

Heat networks can provide a cost-effective source of low-carbon heating, most likely in urban areas with high population density.

9.1.2. INFLUENCING FACTORS AND DEPENDENCIES

As the Welsh energy system transitions to Net Zero, there will be extensive changes to networks. Significant reinforcement of the electricity transmission and distribution networks will be required and new networks will also need to be developed (e.g., heat networks, and potentially hydrogen networks if natural gas networks are not repurposed). Key factors influencing how these networks develop include:

- Extent and location of electricity network reinforcement will depend on variables such as location of generation, how peak heat demand is managed, and how hydrogen is produced.

- Local distribution networks and the transmission network may need to accommodate large electrolyser demands and ensure local constraints are not exacerbated by a collection of these electrolysers around areas with high offshore wind concentration. Conversely, siting electrolysers in areas with electricity transmission network constraints could help reduce these by converting electricity to hydrogen and removing it from the electricity network.
- Individual industry choices will impact level of natural gas and hydrogen consumption in Wales by 2050 and therefore the extent of the gas or hydrogen transmission networks needed.
- The extent and location of a hydrogen network will depend on the level, location and type of hydrogen consumption and how and where hydrogen is produced in Wales (e.g., in the North from biomass and/or nuclear, or the South from electrolysis).
- The deployment of heat networks will result in reduced energy demand for residential properties from other networks. Depending on the type of heat network deployed, the energy centre producing the heat could require localised network infrastructure upgrades (most likely to the local electricity distribution network).

9.2. EVIDENCE

9.2.1. ELECTRICITY IMPORTS AND EXPORTS

Figure 17 and Figure 18 show electricity consumption and production respectively for Wales in 2050 at different times of the day for summer, winter and peak periods (a period of high winter demand combined with low wind generation) for the 'Renewable Electricity 1.25 x electricity consumed' sensitivity scenario. In this sensitivity scenario, annual renewable electricity production in Wales is 1.25 times the annual electricity consumed in Wales.

Together, Figure 17 and Figure 18 show that Wales remains a net exporter of electricity in most modelled time periods. Figure 17 shows total Welsh electricity consumption (green bar) – it then also shows that in most daily time periods electricity is being exported (denoted by the blue bar). However, even in this sensitivity scenario with particularly high levels of renewable generation, there were some time periods within a day where Wales would require electricity imports from England, and during these periods no electricity can be exported. Note that ESME models multiple example days, so this is not suggesting it would happen every day, but on a typical day during the winter or peak period, the modelling suggests there would be some electricity imports.

Figure 18 confirms this. It shows total Welsh electricity generation (blue bar) and for the same period, where no electricity is being exported, it shows imports denoted by the pink bar. Lower wind outputs coupled with higher demand periods (i.e., winter and peak periods) result in the need to import electricity, which may put pressure on the rest of the GB system in these periods. Otherwise, Wales remains a net exporter in the remaining time periods. Whilst energy storage in Wales could help to remove the need for import, the demand to be met at peak times is significant and could occur with wind generation at lower than 20% of maximum capacity. This means that gaseous geological scale storage may be required which is likely to be sited in England.

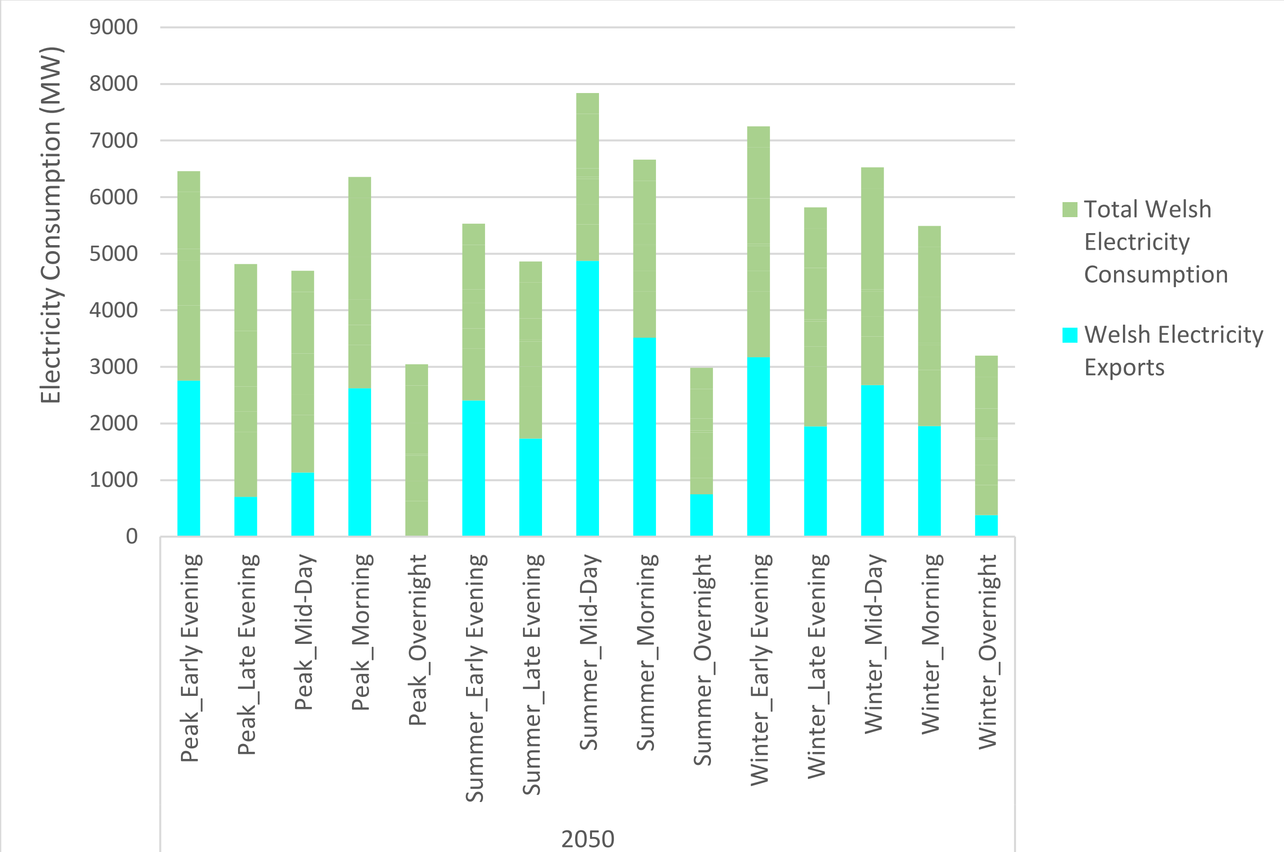

Figure 17: Electricity consumption in Wales for different time periods across a year, showing electricity exports for most periods 2050 – 'Renewable Electricity 1.25 x electricity consumed' sensitivity

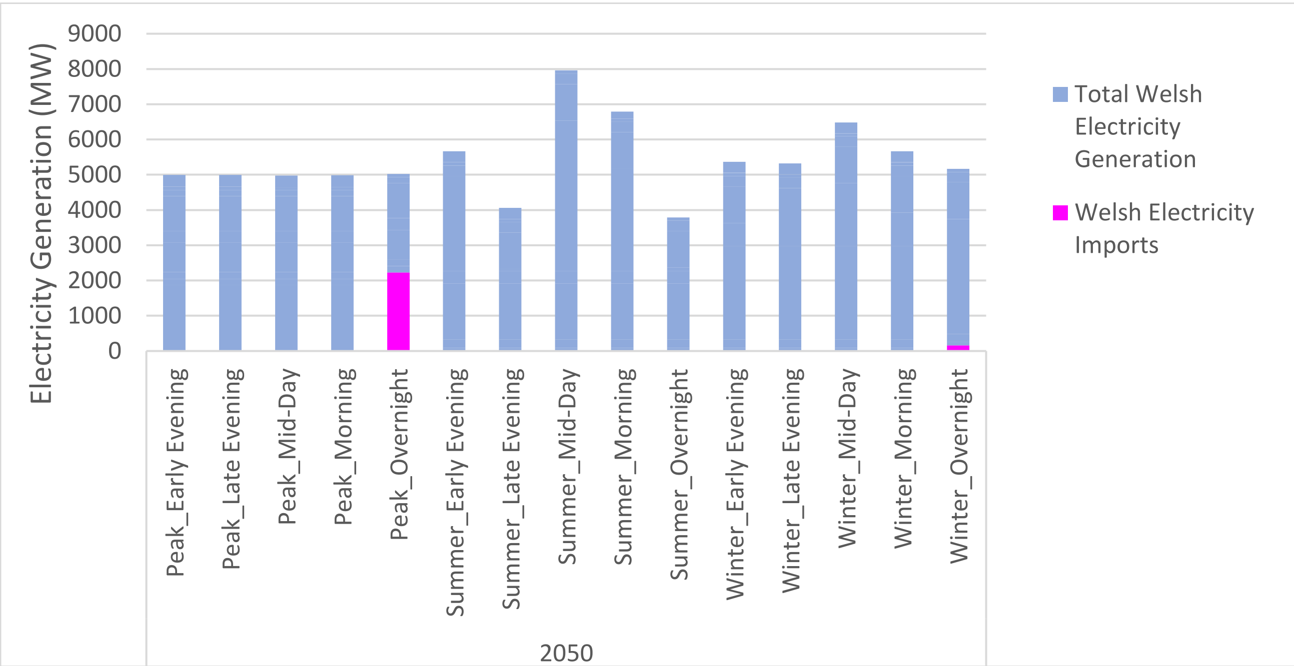

Figure 18: Electricity production in Wales for different time periods across a year, showing when electricity imports are needed for 2050 – 'Renewable Electricity 1.25 x electricity consumed' sensitivity

Wales is currently a net exporter of electricity. Although some of the analysis in this project suggests Wales may become a net importer in intermediate years, modelling undertaken suggests it is likely to again be a net exporter from the 2030s (see section 8.2). This would align with the assessment made by the NGESO around the eventual need to strengthen the export capabilities of the transmission electricity infrastructure on the border between England and Wales[66].

Depending on system conditions and the time period, the local electricity distribution network would need significant but varying levels of reinforcement and flexibility to manage large volumes of generation exporting on to the transmission system. This has also been confirmed by networks during stakeholder engagement and is consistent with the Distribution Future Energy Scenarios (DFES) (e.g.,[67]). The level of reinforcement required at the local level and pathways for the networks would depend largely on the adoption rates of different technologies and the development of policies that may influence the adoption of Low Carbon Technologies (LCTs) on the distribution network and "behind-the-meter" at homes and businesses.

Statements gathered from network operators during stakeholder engagement throughout the project reinforce the findings of the modelling and analysis undertaken for this project. Physical reinforcement of the networks will be needed alongside deployment of smart and flexible energy systems, to shift or reduce peak loads and better manage the demands of a Net Zero energy system.

9.2.2. TRANSMISSION AND DISTRIBUTION ELECTRICTY NETWORKS

The electricity transmission networks across GB need significant reinforcement to deal with the long-term transition to high volumes of offshore wind. Reinforcement will need to accelerate in the 2030s as the levelised cost of offshore wind continues to fall and Welsh electricity demand continues to increase. NGESO's HND looks at the network infrastructure needed to connect an additional 23 GW of offshore wind by 2030. It shows new network requirements across GB including in North and South Wales. With further deployment of offshore wind expected after 2030, including significant potential in the Celtic Sea, it is likely additional network reinforcement will be needed beyond this.

Decision making around transmission and distribution network reinforcement needs to happen immediately. This view has been reinforced by Ofgem's ASTI[68] consultation, which is looking to expedite large strategic onshore electricity transmission projects. The Department of Energy Security and Net Zero (DESNZ) appointed Nick Winser as the Electricity Networks Commissioner (ENC)[69], to identify options to reduce the time it takes to identify the need for and build onshore electricity transmission assets. This will be key to enabling the generation investment required. Transmission reinforcement is already creating bottlenecks in generation deployment and it will be important that distribution networks move at pace in the RIIO-ED2 price control to avoid connection times spiralling and stalling the transition.

In all scenarios an increase in peak electricity consumption in Wales suggests that electricity distribution network reinforcement is likely to be required across much of Wales. This is also evident within the Long-Term Development Statement (LTDS) submitted by the respective DNOs

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[66] South Wales and South England boundaries, NGESO https://www.nationalgrideso.com/research-publications/etys/electricity-transmission-network-requirements/south-wales-england-boundaries

[67] SP Manweb Future Energy Scenarios, SP Energy Networks (2022) https://www.spenergynetworks.co.uk/userfiles/file/DFES_SP_Manweb_December_2022.pdf

[68] Accelerated Strategic Transmission Investment Informal Licence Drafting Consultation, Ofgem (2023) https://www.ofgem.gov.uk/publications/accelerated-strategic-transmission-investment-informal-licence-drafting-consultation

[69] New Electricity Networks Commissioner appointed to help ensure home-grown energy for Britain, UK Gov (2022) https://www.gov.uk/government/news/new-electricity-networks-commissioner-appointed-to-help-ensure-home-grown-energy-for-britain

which contain all the network plans over the next 10-years, as well as RIIO-ED2 submissions until 2028. DNO Network Development Plans (NDPs) also contain detailed summaries of DNO interventions, capacities at sites until 2050 and how the plans have been formulated via methodology statements.[70] [71]

Specific locations and the extent of electricity network reinforcement will depend on technology preferences, particularly for heating and industry, and network preparedness for multiple solutions will be required. An example of this is the need to prepare networks for a large landing of offshore wind potentially in both North and South Wales (Technology-Optimistic and Societally Optimistic deploy 10-13GW of offshore wind connecting to Wales by 2050 – see section 8.1.1), and if green hydrogen production is to accompany offshore wind, the location and specific pinch points on the networks will need continual monitoring and assessment.

Planning for more cohesive and widespread electricity transmission system reinforcements will be covered by the NGESO in the Centralised Strategic Network Plan (CSNP). Whilst the CSNP does not directly address the distribution networks, its impact will have direct effect on how local networks are planned and how LAEPs are developed.

There should be a concerted effort to align distribution and transmission developments for the future Welsh Energy Grid. The networks will continue to assess optimal solutions to facilitate the above. They should engage with Welsh Government and Local Authorities to explore the impact of different future energy choices and pathways, some of which are explored in this report.

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[70] Network Development Plan, SP Energy Network (2022) https://www.spenergynetworks.co.uk/pages/network_development_plan.aspx
[71] Network Development Plan, Western Power (2022) https://www.nationalgrid.co.uk/downloads-view-reciteme/557686

9.2.3. NATURAL GAS AND HYDROGEN NETWORKS

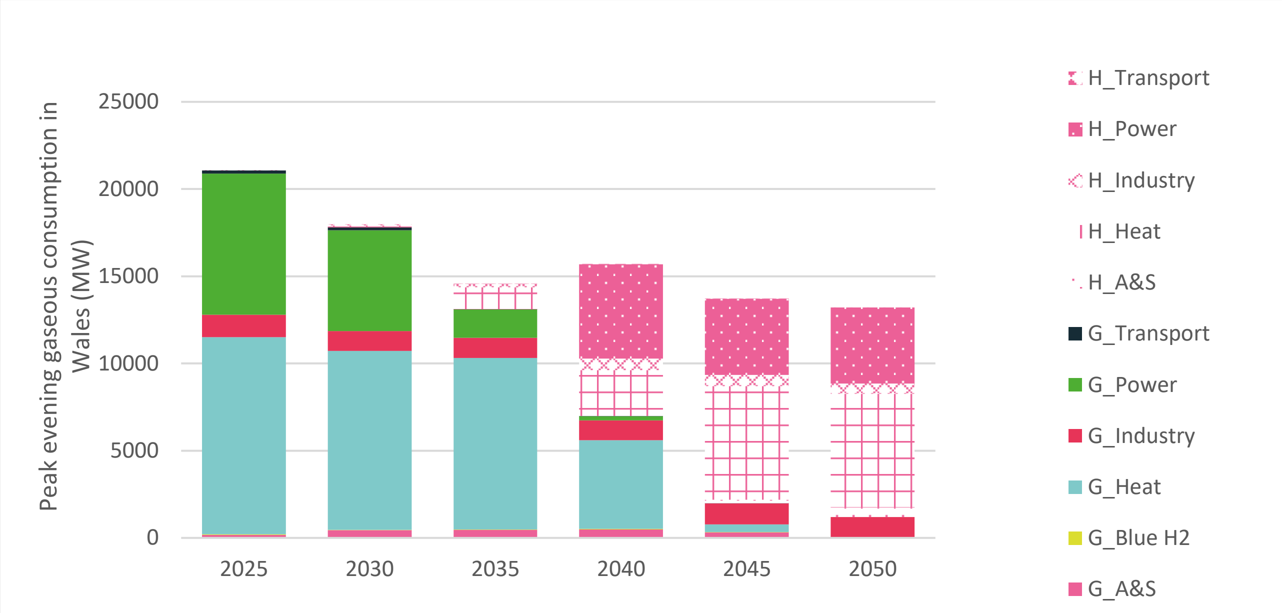

Figure 19: Technology-Optimistic (TOC) scenario illustrating gaseous peak consumption in MW, showing both natural gas (G in the legend) and H_2 (H in the legend) consumption. H_2 consumption is relatively large as it is used for the decarbonisation of heat

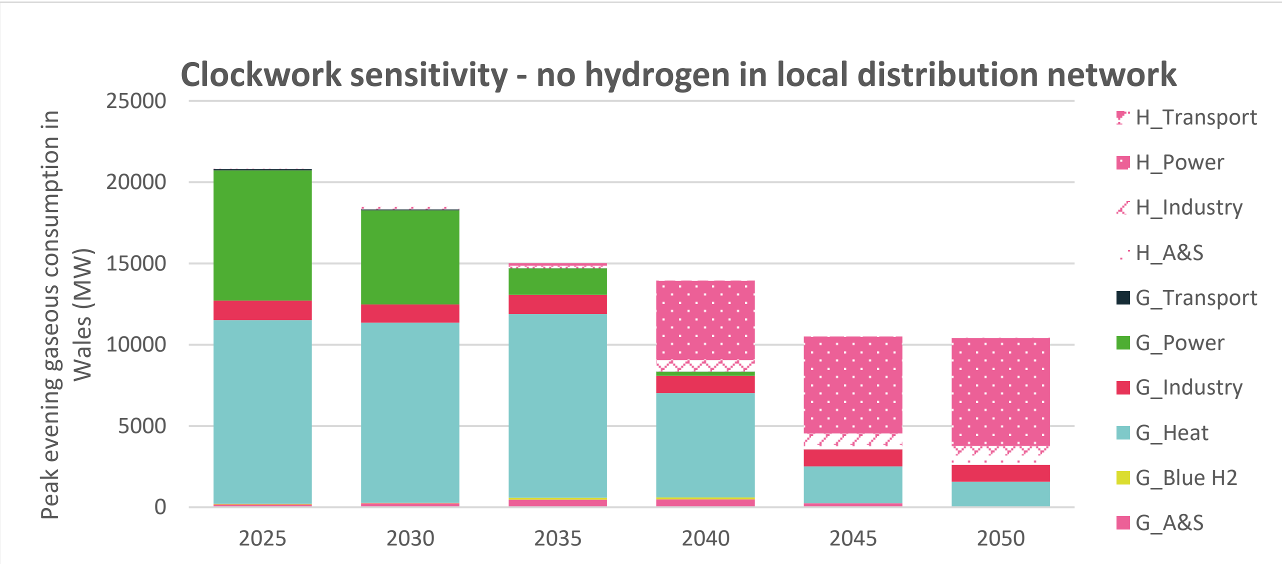

Figure 20: 'No H2 Repurpose' scenario – a sensitivity conducted where H_2 was removed in local distribution networks, which resulted in minimal H_2 usage for heat but increasing H_2 use for power production i.e. H_2 peaking plants (note this scenario was not consistent with a Net Zero energy system). Shows both natural gas (G in the legend) and H_2 (H in the legend) consumption.

Together, Figure 19 and Figure 20 show peak evening natural gas and hydrogen consumption in Wales by sector from 2025-2050 for the Technology-Optimistic scenario (Figure 19), and a sensitivity where there is no hydrogen on the local distribution network ('No H2 Repurpose' sensitivity scenario) (Figure 20). In these figures the solid-filled bars relate to natural gas consumption, and the patterned-filled bars relate to hydrogen consumption. Note these are peak consumption values and do not necessarily reflect how total energy demand over the course of a year is met. Instead, they provide an indication of the networks required to support meeting peak demand.

Figure 19 shows that by 2050 natural gas consumption is small and limited to industry use. This indicates that a natural gas distribution network will not be required, although it may be repurposed, either fully or in part to distribute hydrogen, most likely for heating.

Hydrogen is meeting peak demands from heat and power, and to a lesser extent also from aviation, shipping and industry – the majority of total hydrogen consumption is for aviation, shipping and industry but this is largely not during peak times. Hydrogen for power and industry is likely to sit on the transmission level of any energy network and any hydrogen export potential from Wales to the rest of GB, or other global markets, will also require a transmission network.

While there are uncertainties around the use-case for hydrogen in each of these sectors, given that there are three distinct uses, it is likely that it will be used for at least one of these. This shows that a hydrogen transmission network will likely be required (see section 16) – this finding held across all scenarios modelled. This transmission network will need to link to hydrogen storage. As there are currently no storage options in Wales[72], it is assumed it will connect to storage in England to allow hydrogen imports to support low-wind periods. This transmission network could also allow hydrogen exports to the rest of GB which provides an economic opportunity to Wales.

Domestic heat demand requires a distribution network and so Figure 19 also suggest that a hydrogen distribution network will be required in Wales. This was tested further by the scenarios shown in Figure 20 where a hydrogen distribution network was not built. The location of any hydrogen distribution network is uncertain, with many influencing factors such as role for hydrogen for heating, whether the gas distribution network is repurposed and local topography, and this is explored more in Section 14.

This figure shows that if hydrogen is no longer meeting heat demand, there is an increased demand from the power sector for hydrogen. This is because more electricity is needed to help meet peak heat demand. In this scenario some peak demand for natural gas for heat also remains but CCS cannot be applied at a domestic scale and therefore this scenario does not meet Net Zero. However, as discussed in Section 6, there are a number of uncertainties around how peak heat demand will be met and the role of hydrogen in meeting it, and the extent to which consumer behaviour and choices around comfort at home as well as innovation in design and integration of low carbon heating technologies will develop.

Whilst these uncertainties must be recognised and explored, the analysis shown in Figure 19 and Figure 20 suggest that some level of hydrogen distribution network is required to meet some peak heat demand.

9.2.4. HEAT NETWORKS

The analysis carried out in this project shows that district heating plays an increasing role in meeting heating demand. This is expected to be predominantly in urban areas with high population density, or areas near a large heat source (e.g., a nuclear power plant). In these areas, multiple homes can be supplied with hot water for space heating through a network of insulated underground pipes. In this analysis these networks are heated by large-scale heat pumps or nuclear cogeneration and supplemented by peaking boilers (fed first by natural gas and then by hydrogen) and storage, but other sources such as waste heat from industry could also be used.

[72] This project has generally assumed that large-scale geological hydrogen storage would be in England, however it is recognised that work is underway to explore potential sites in Wales – see section 14.2.2 for more detail.

Local analysis will be required to refine specific locations for practical heat networks based on population density and proximity to heat production (see section 6.3).

9.3. RECOMMENDATION

Recommendation 6: Set out the preferred energy system outcomes, where appropriate, to provide more clarity on the Welsh energy system transition .

Welsh Government should provide leadership and minimise uncertainty where appropriate and possible by continuing to set out its priority outcomes for the Welsh energy system (e.g., providing economic benefits to Wales; ensuring environmental sustainability; encouraging people to insulate their homes). This will help provide clarity as to how these priorities could impact the system and energy networks in the future. This is a broad recommendation which stretches across the energy system, but key areas where Welsh Government could facilitate and set out priorities include network connection routes and decarbonisation priorities:

- The routing of network connections for offshore and onshore wind is still uncertain. Whilst planning permission for transmission networks is not devolved, Welsh Government should work with network operators to inform citizens of the potential benefits, or negative impacts, network routes may bring. For example, providing more network connection opportunities for Wales or enabling an offshore wind industry that may provide skilled jobs, or adverse environmental impacts.
- Welsh Government should review and explore how existing and future top-down priorities relating to the whole Welsh energy system align with those priorities coming from the bottom-up process of Local Area Energy Plans (LAEPs), which are due to be completed next year. Welsh Government should then work with TSOs, DNOs and GDNs, LAs, business, and industry to deliver on these priorities. This process of considering priorities from a top-down and bottom-up perspective will provide a greater degree of confidence in making anticipatory investment decisions.

10. KEY INSIGHT – ELECTRICITY TRANSMISSION – WELSH NORTH SOUTH LINK DRIVERS AND OPPORTUNITIES

10.1. INSIGHT

Building a Welsh North-South transmission system link would present a number of opportunities for Wales.

10.1.1. SUMMARY OF ANALYSIS

The Welsh North-South link is a critical infrastructure project and is required for GB to meet the offshore wind capacity target of 50GW by the end of 2030. It is recognised by NGESO in the HND that the estimated delivery time is beyond 2030 but NGET, who will develop the link, are aiming to accelerate delivery of the project[73]. Additionally, the Electricity Networks Commissioner aims to identify options to reduce the time it takes to identify the need for and build onshore electricity transmission assets.

The North-South link has the potential to support meeting the increasing electrification of energy demand, and decarbonisation of energy supply, in Mid Wales. This could reduce emissions and support the transition to a low-carbon energy system. The construction and operation of the North-South link could create job including jobs in construction, operation, and maintenance of the link, as well as in industries that could grow given greater access to the electricity network.

10.1.2. INFLUENCING FACTORS AND DEPENDENCIES

The North-South link could provide a number of benefits to Wales, particularly Mid-Wales. These benefits are dependent on the route chosen being onshore rather than offshore. An onshore route is likely to provide opportunities for Wales in terms of enabling more low-carbon generation assets to connect to the network and supporting distribution network reinforcement (although it is transmission infrastructure itself). An offshore route however, is likely to have less environmental impact such as impact on visual amenity.

Electricity demand in Mid-Wales is currently relatively low, and there is no high voltage transmission infrastructure in the region (see Figure 21). The analysis carried out in this project suggests that, compared to other regions, there will be a relatively modest peak demand increase in Mid-Wales, between 245MW and 290MW from 2025-2030 under the baseline scenarios.

Although modest, the increase in demand will require distribution network reinforcement. This has been supported by this projects stakeholder engagement with the network operators. Building the North-South transmission link in Mid-Wales would support the distribution network reinforcement, mainly by potentially providing more Grid Supply Points (GSPs) from which the distribution network could be built out. In turn this can provide additional stability and network security by allowing DNOs to interconnect radial sites to new GSPs.

Whilst the North-South link or other transmission infrastructure reinforcement would benefit Mid-Wales, the increase in demands alone may not warrant electricity transmission infrastructure being built.

The route of the link could be designed to connect areas of high renewable energy potential (e.g., offshore wind farms) to the grid. This would include opportunities for onshore wind if there are

[73] A Holistic Network Design for Offshore Wind, NGESO https://www.nationalgrideso.com/future-energy/the-pathway-2030-holistic-network-design/hnd

optimal sites (i.e., in terms of wind resource profiles). The link could be built onshore or be a mix of onshore and an offshore sea-based cable depending on final design outcome after NGET have consulted on the route for the infrastructure.

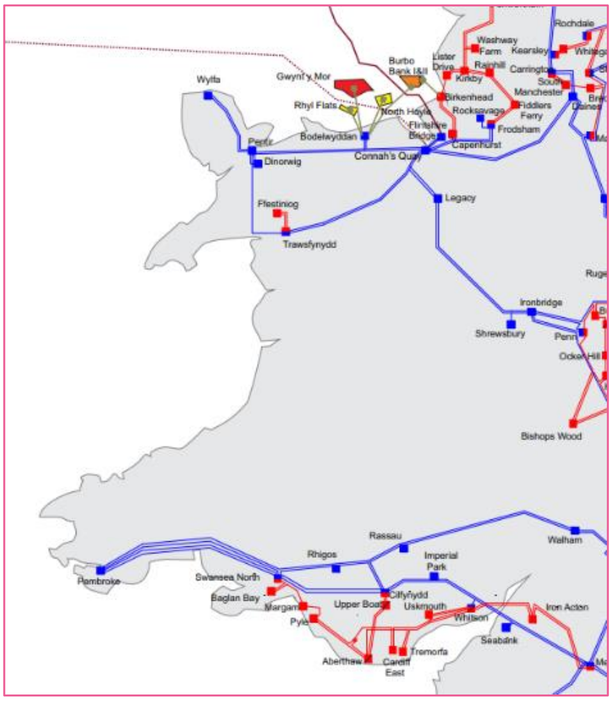

Figure 21: The current state of the Electricity Transmission System in Wales, (no transmission infrastructure in Mid-Wales). [74]

10.2. EVIDENCE

The HND and Network Options Assessment Refresh (NOA Refresh) published in 2022 called for the PNSC (NOA Project code for the North-South Link) to be built to meet the 50GW offshore wind by 2030[75]. Figure 22 illustrates the need for connection in the form of a purple dotted line north to south Wales, indicating the network need and not the route. Route options have not yet been confirmed.

The infrastructure is due to be built by 2037 but NGET are looking at ways to accelerate delivery and working collaboratively with appropriate stakeholders to explore this.[76]

Whilst the North-South link is part of the electricity transmission network, more generally, a whole system approach should be applied to the planning and development of the Welsh energy system. This should consider longer-term efficient and coordinated solutions for Wales, including Mid Wales, across all electricity and natural gas transmission and distribution networks, as well as other energy network (e.g., heat networks, hydrogen networks, etc.).

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[74] System Schematics and Geographic Drawings, NGESO (2022)
https://www.nationalgrideso.com/document/275581/download
[75] Network Options Assessment 2021/22 Refresh, NGESO (2022)
https://www.nationalgrideso.com/document/262981/download
[76] Decision on accelerating onshore electricity transmission investment, Ofgem (2022)
https://www.ofgem.gov.uk/publications/decision-accelerating-onshore-electricity-transmission-investment

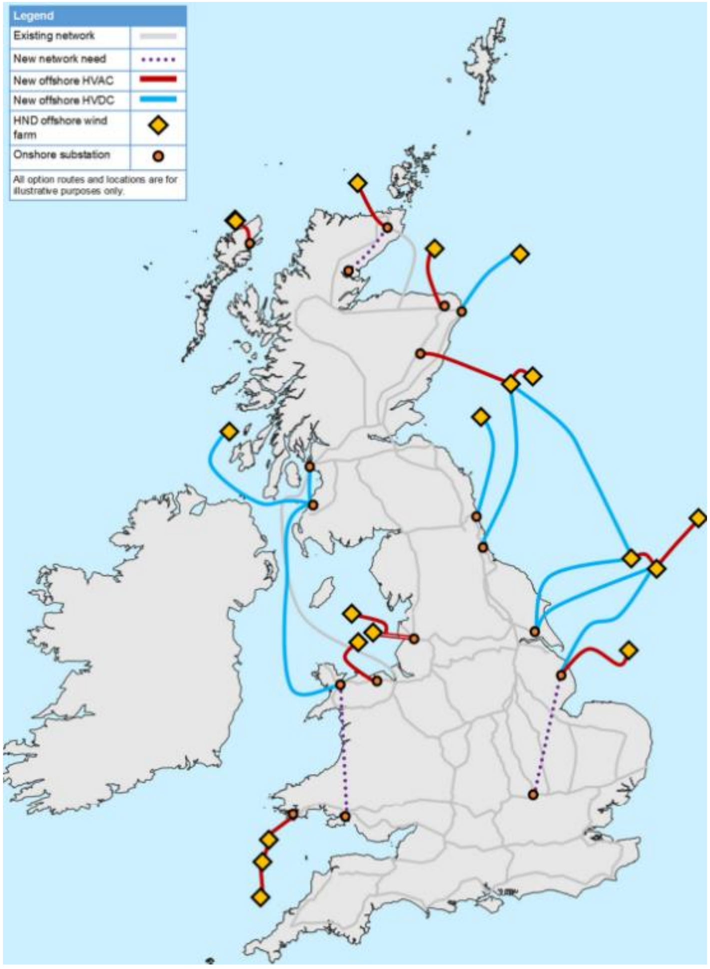

Figure 22 : HND Network Needs, Illustrating the North-South Link – Courtesy, HND, NGESO

10.2.1. GROWTH OF RENEWABLES AND LINK TO MIDWALES

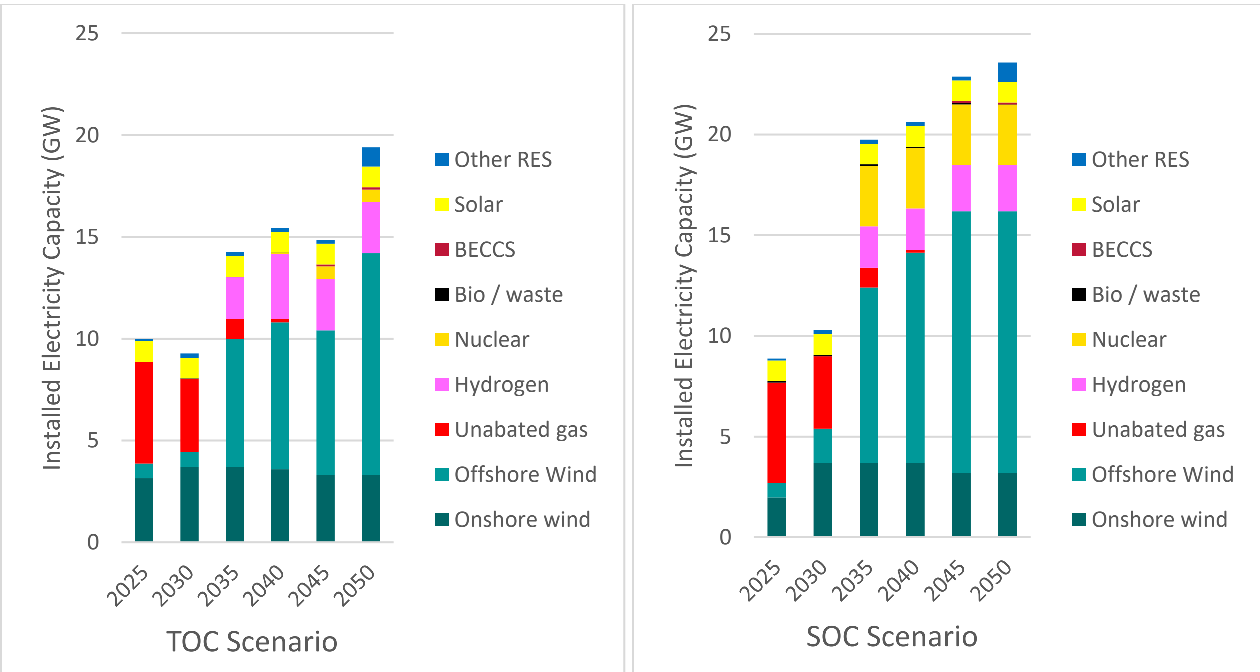

Figure 23: Installed electricity generation capacity in Wales 2020-2050, left: Technology-Optimistic (TOC), right: Societally Optimistic (SOC) scenarios

Both baseline scenarios for this analysis (Technology-Optimistic and Societally Optimistic: Figure 23) showed a significant increase in renewable generation capacity. Between 2030 and 2040, offshore wind is expected to grow significantly, resulting in up to 13GW by 2050 (Societally-Optimistic). The ESME model does not undertake power system analysis and so does not provide detail on network infrastructure requirements, however this increase in offshore wind aligns with publications like the HND and the FES [77] and the need for the North-South link.

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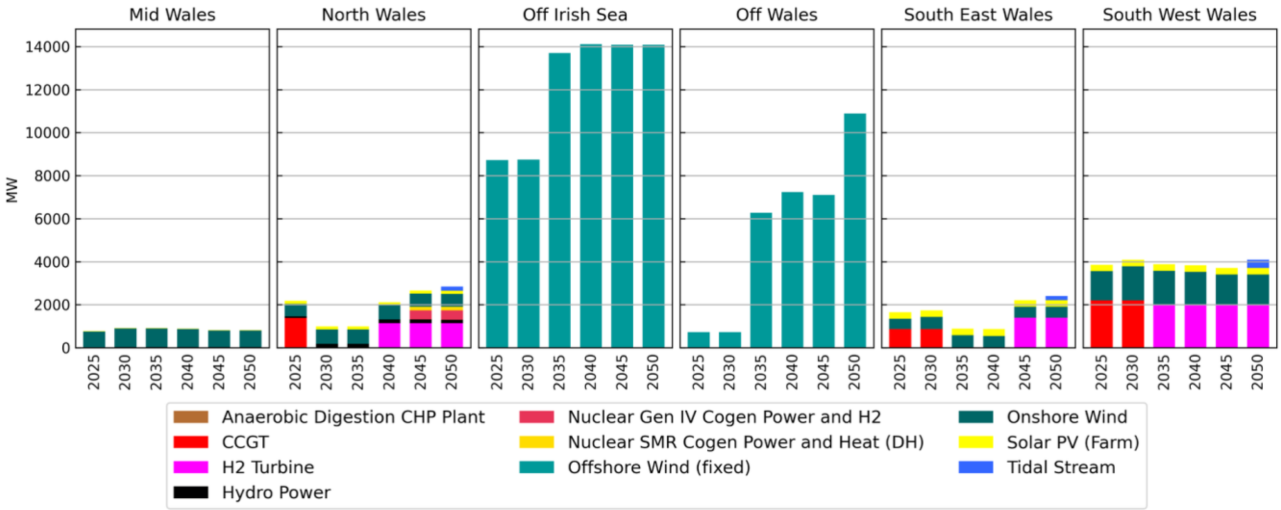

Figure 24: Technology Optimistic scenario with a Breakdown of Generation Type Installed by Region

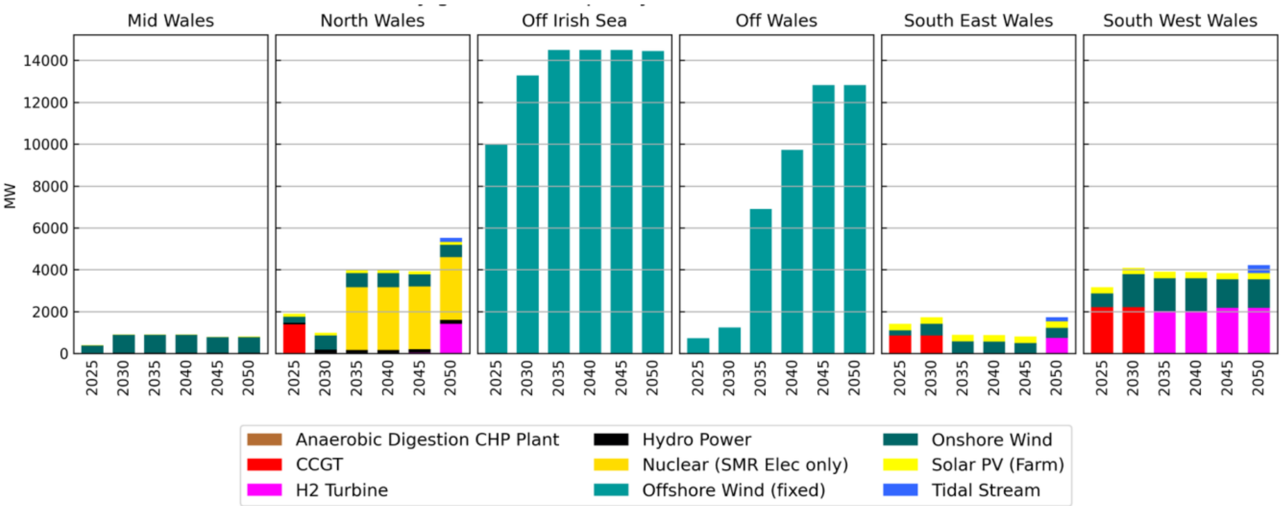

Figure 25: Societally Optimistic Scenario with a Breakdown of Generation Type Installed by Region

Figure 24 and Figure 25, use ESME Networks to show electricity generation capacity out to 2050 on a regional scale for Technology-Optimistic and Societally Optimistic. This further highlights the level of renewable generation, particularly offshore wind which may be deployed by 2050.

The scenarios explored within this project include deployment of up to 13GW of offshore wind that is directly connected to Wales by 2050. However, more than double this capacity of offshore wind could be deployed within the Irish and Celtic seas overall, with some of this generation landed in England and some in Wales. The modelling using ESME of where to deploy and connect offshore

[77] Future Energy Scenarios, NGESO (2023) https://www.nationalgrideso.com/future-energy/future-energy-scenarios

wind undertaken for this project is based on a broad consideration of factors including proximity to demand centres, transmission and distribution connection requirements and distance offshore. This omits some of the local factors that could prompt connection in preferred locations. Additionally, the HND has suggested that offshore wind in the Celtic[78] and Irish seas could extensively connect to Wales.

Given these points, and to highlight the maximum potential of offshore wind to connect to Wales we have included all offshore wind capacity in these areas in the ESME Networks modelling outputs shown in Figures 24 and 25. This has not be done for the ESME modelling which represents ESC's best view of a least cost system, rather than the maximum potential of offshore wind .The inclusion of this additional wind capacity is limited to the analysis shown in Figure 24 and Figure 25 and does not influence any of the other analysis shown in this project, such as that related to electrification of transport and heat.

Many properties in Mid Wales are off the gas network and are connected to a mostly 11kV distribution network, as can be seen in Figure 26 below. If the Mid Wales areas are reinforced through High Voltage transmission infrastructure, this could provide the infrastructure needed to enable households in Mid Wales to electrify their heating and transport demands (currently met by predominantly oil and liquid fuels, respectively). It also offers the opportunity for increased onshore wind and solar.

New 132kV lines may be built on new Grid Supply Points (GSPs) that could be based along the North-South Link were it to pass through Mid-Wales. This could also include feeders for electric trains or public transport depots, as well as the development of large heat pump or even hybrid energy centres supplying heat networks in local communities with sufficient heating demand.

[78] Offshore wind in the Celtic sea is referred to as "Off Wales" in Figures 24 and 25

Figure 26: Red lines illustrate the 132kV distribution infrastructure in Mid-Wales, with Gold and Green representing 66kV and 11kV respectively. – Courtesy, OpenInfraMap

Figure 26 illustrates the limited 132kV infrastructure in Mid-Wales which is what most generation is connected to. Many areas in Mid-Wales have off-grid gas properties that could be electrified were greater access to GSPs presented via the North-South Link. Existing plans for development in this area include the Ferryside GSP and 132KV circuit works into Mid-Wales that have been submitted by NGED as part of their RIIO-ED2 business plan[79].

[79] NGED Business Plan 2023-2028 - SA-06a - Supplementary Annex - Load Related Expenditure. https://yourpowerfuture.nationalgrid.co.uk/downloads/42117

10.3. RECOMMENDATION

Recommendation 7: Actively explore and communicate the benefits of a North-South electricity transmission connection.

The route of the North-South electricity transmission link has not yet been determined. Transmission lines can be controversial and face local opposition. The Welsh Government can demonstrate leadership, act as a convening institution and help bridge the different perspectives of citizens impacted by routing options. Welsh Government should engage with NGET to convene and feed-in the views of Welsh stakeholders around potential routes during the initial stages of design.

This should include the key consideration that if an onshore route is chosen, rather than an offshore route[80], there is the potential for improved network connection opportunities in Wales (e.g., opening up the potential for connections for solar and onshore wind generation). Any negative impacts of specific routes, or types of routes, should also be considered. For example onshore routes may have a greater environmental impact (e.g. impact on visual amenity). This could support Wales to achieve its ambitions, unlocking certain decarbonisation options and helping Wales prosper from the transition, developing skills, and supporting economic growth and community energy.

[80] "Onshore" electricity transmission lines (i.e., transmission lines not connecting offshore assets to the onshore grid) can be routed offshore to avoid some of the challenges faced from purely onshore routes.

11. KEY INSIGHT – THE ROLE OF KEY DEMAND-SIDE INTERVENTIONS TO REACH A NET ZERO WALES

11.1. INSIGHT

Welsh heating and road transport demand will be largely met by electrification. A smart, innovative approach across energy vectors will reduce the level of network reinforcement required to meet peak electricity demand.

11.1.1. SUMMARY OF ANALYSIS

An energy system without demand side flexibility, where energy demand is shifted to match the available energy supply, may prove practically and economically challenging to operate. Key demand side flexibility options include smart EV charging and smart heating, usually enabled by thermal storage.

Where industrial sectors electrify or switch to green hydrogen to decarbonise, they can participate in demand side response (DSR). This involves reducing electricity demand when electricity supply is low and increasing it when supply is high[81].

As well as DSR, other key demand side interventions include insulation retrofits to buildings, and behavioural change to reduce heat demand whilst maintaining thermal comfort. Both of these options can contribute to reducing peak demands, which helps to lower overall system and network costs.

11.1.2. INFLUENCING FACTORS AND DEPENDENCIES

Whilst DSR and demand side interventions can reduce peak demand they must still meet user needs such as thermal comfort levels. This is particularly important for measures which relate to heat demand (i.e., smart heating and behavioural change) where people's expectations around warmth must be met.

Demand side flexibility options such as smart EV charging and smart heating will require intelligent control systems and the development of digital infrastructure to maximise system benefit. The markets and business models needed to incentivise people and businesses to provide demand side response are already starting to materialise. Smarter energy systems could open up economic opportunities for people and businesses in Wales.

11.2. EVIDENCE

The scenarios below show the opportunities for managing peaks from smart charging and heating as well as people behaving differently, both through installing insulation and having technologies that can operate as part of a smart system.

[81] Future Energy Scenarios, National Grid ESO (2022) https://www.nationalgrideso.com/future-energy/future-energy-scenarios

11.2.1. ELECTRIC VEHICLE SMART CHARGING

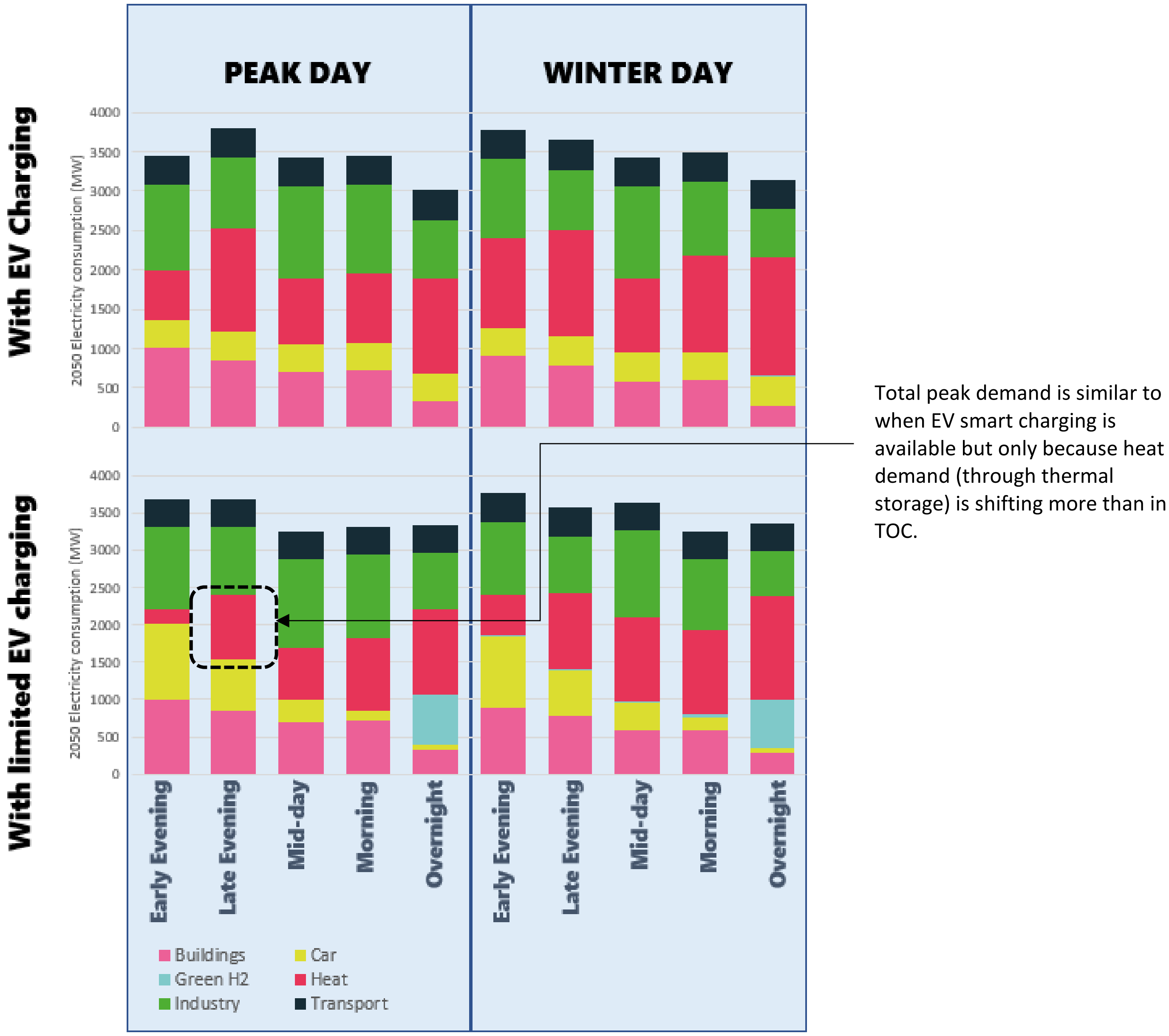

Figure 27: 2050 Electricity consumption, Top: Technology-Optimistic (TOC) scenario vs, Bottom: 'TOC Low EV Smart Charging' scenario (i.e., restricted EV smart charging)

Figure 27 compares the Technology-Optimistic baseline scenario and the ESME sensitivity scenario 'TOC Low EV Smart Charging', for the 2050 period (i.e., one with smart EV charging and the other with limited smart EV charging). All other types of smart response including smart heating were able to operate as the model required.

The charts show the average hourly electricity consumption for periods during the day for a winter day[82] and a peak day[83] in 2050. The highest peak demand is broadly the same for both scenarios and occurs during a winter early evening. However, where EV smart charging is not occurring, the lack of flexibility necessitates the use of additional thermal storage and even drives broader systematic change to ensure least cost systems – in this case, there is an uptake of hydrogen

[82] A "winter day" in ESME represents a typical winter day with average demands experienced over a winter period
[83] A "peak day" in ESME represents a day of system stress with high winter demand and low renewable supply

production overnight (when electricity supply is typically higher than demand) to meet peak heat demand (typically evening periods) through a hybrid heating system.

If peak demand is allowed to increase instead, this also increases system costs as more generation and more network reinforcement is required. EV smart charging is therefore a lower cost measure to manage peak demand. This aligns with the GB Government ambition for "Widespread EV smart charging [which] keeps costs down for all electricity bill payers, whether they own an EV or otherwise"[84].

11.2.2. SMART HEATING

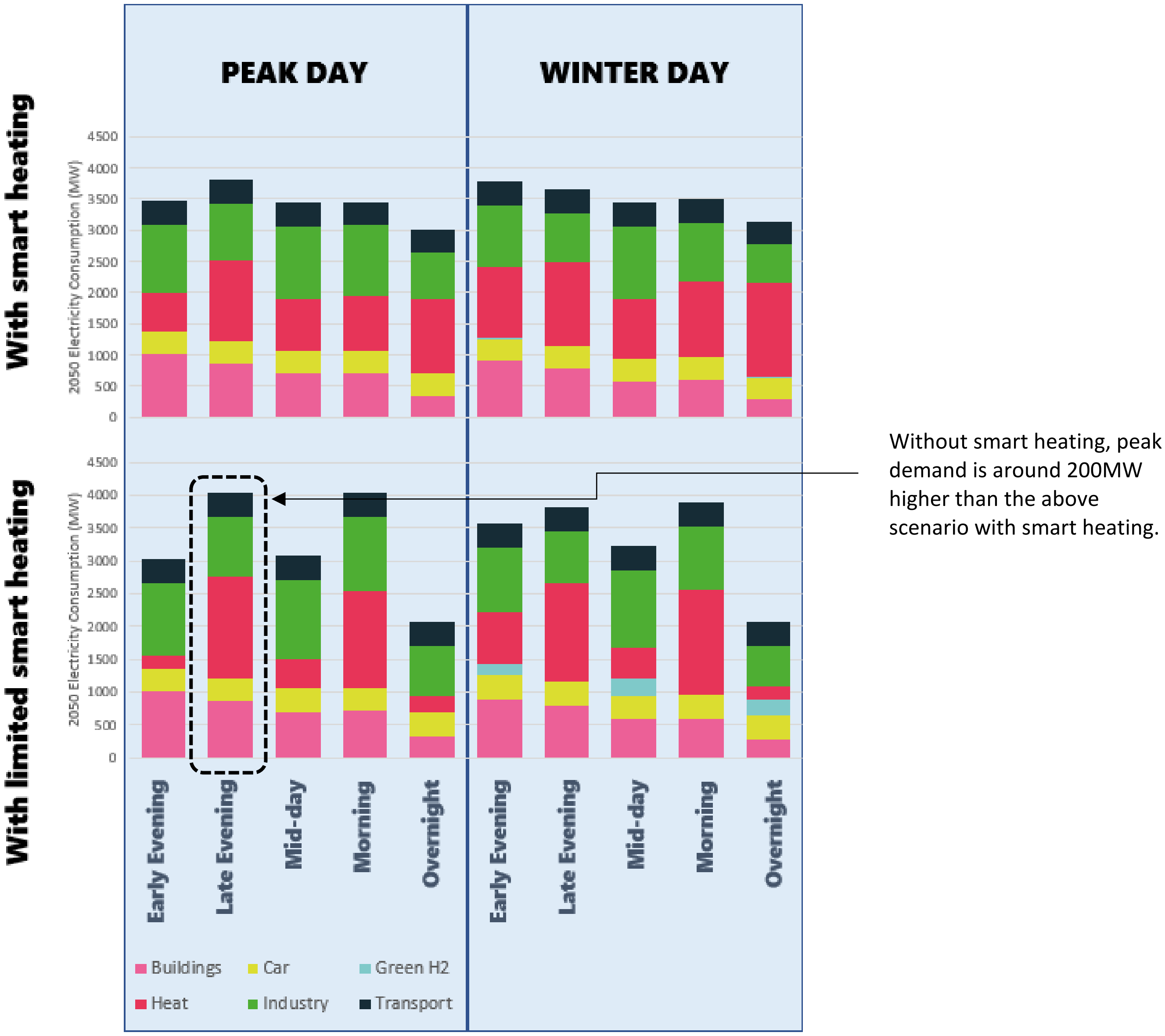

Figure 28: 2050 Electricity consumption, Top: Technology-Optimistic (TOC) scenario vs, Bottom: TOC Low Heat Storage scenario (e.g. restricted smart heating)

[84] Electric vehicle smart charging action plan, UK Government (2023) https://www.gov.uk/government/publications/electric-vehicle-smart-charging-action-plan

Figure 28 compares the Technology-Optimistic baseline scenario in 2050 with the sensitivity scenario ''TOC Low Heat Storage' (i.e., one with smart heating and the other with limited smart heating which restricts behind-the-meter heat storage and therefore smart heating)[85]. The figure shows the average hourly electricity consumption in 2050 for periods during the day for a winter day and a peak day with limited smart heating. Demand is about 200MW (5%) greater than with smart heating. As with EV smart charging, reducing peak demand requires less generation technology to meet peak demand and network reinforcement, reducing total system costs.

11.2.1. BUILDING INSULATION RETROFITS

Figure 29 below shows peak demand over a year on the electricity distribution network for 2030-2050. Note, most of the total annual heat demand is met by electricity, as described in Section 6. These figures provide an indication of the networks required to meet this peak demand.

Figure 30 shows three scenarios: Technology-Optimistic (left), 'TOC Retro Ultra Low' (center) which assumes retrofits are at an "ultra-low cost", and 'TOC Retro Early' (right) which assumes a similar retrofit deployment trajectory as 'TOC Retro Ultra Low', but happening a decade earlier. Retrofit refers to a whole-house package of insulation measures that vary by property type but typically include measures such as loft insulation, wall insulation and draught proofing[86]. More numerous or earlier retrofits reduce peak demand on the electricity network by over 400MW (10%) by 2050.

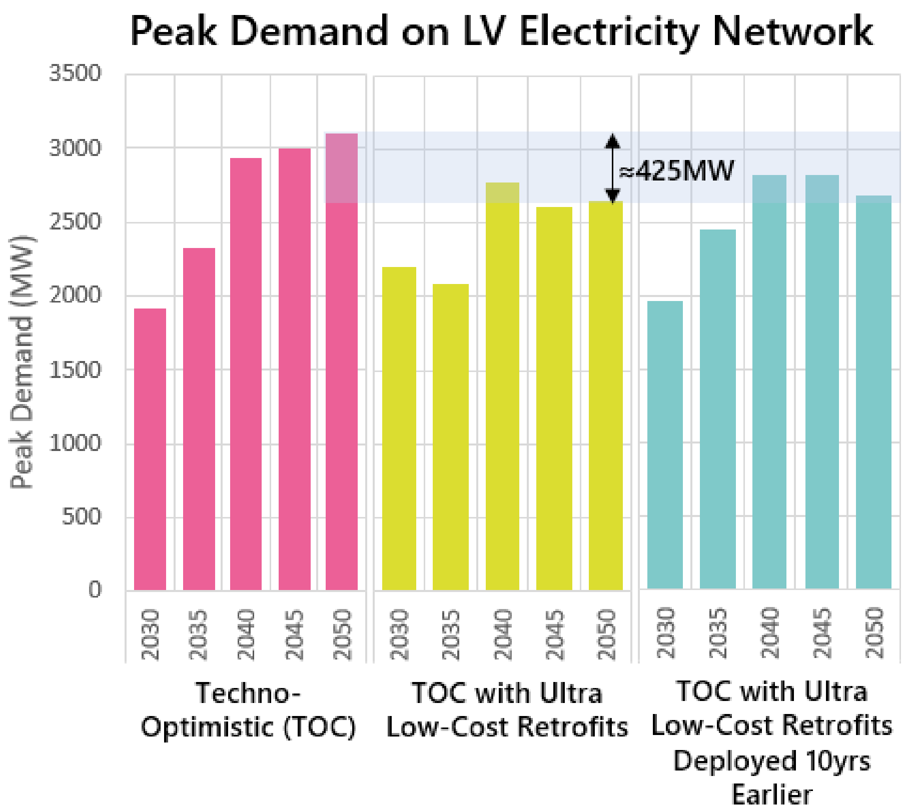

Figure 29: Peak demand in 2050 for left: Technology-Optimistic (TOC) scenario vs, central: 'TOC Retro Ultra Low' scenario (low cost insulation retrofits) vs, right: 'TOC Early Retro' scenario

[85] In the ESME scenarios assessed, while EV's can charge in a smart way, the profile for this charging is fixed and cannot adjust in response to other changes, for example restricted smart heating.
[86] Whilst it will vary by house these retrofit levels typically reduce fabric heat loss by up to 50%.

11.2.2. BEHAVIOURAL CHANGE

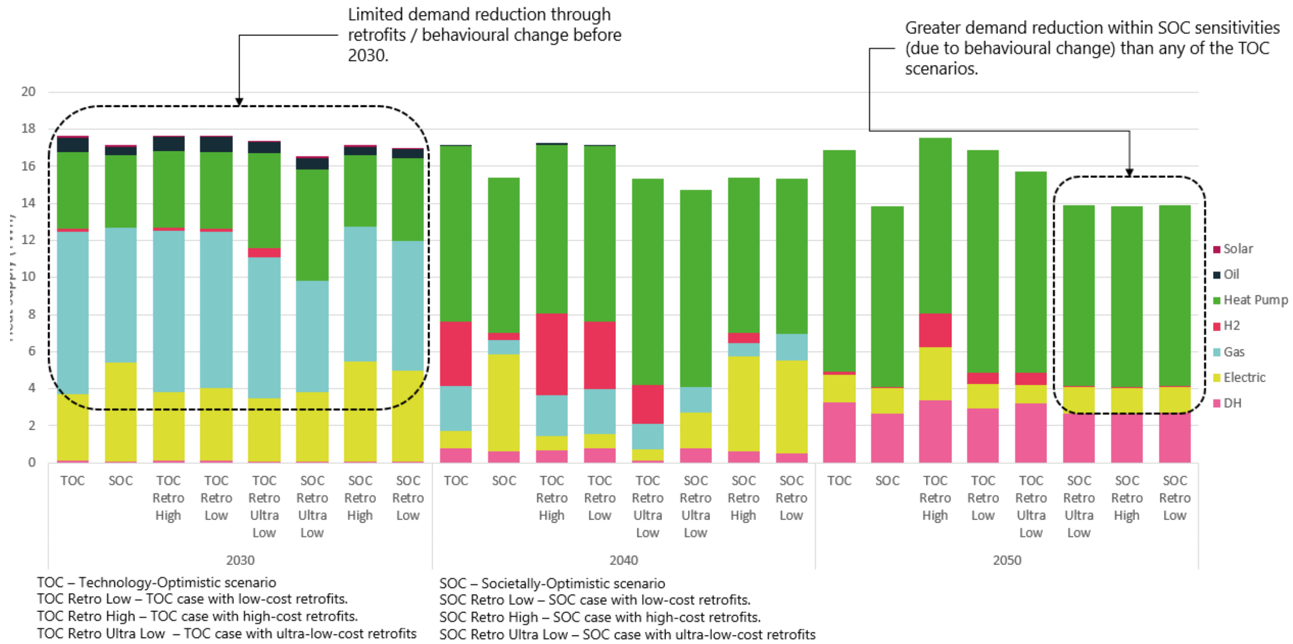

Figure 30: Annual heat supply for Technology-Optimistic (TOC), Societally Optimistic (SOC) and a number of sensitivity scenarios

Figure 30 shows annual heat supply for 2030, 2040 and 2050. It shows Technology-Optimistic, Societally Optimistic and a number of sensitivity scenarios where building insulation retrofit levels have been increased or decreased by varying the cost of retrofits. These sensitivities are included as building insulation is a key factor in varying heat demand. As described in the figure annotations, from 2040 onwards Societally Optimistic and the sensitivities based on Societally Optimistic have a lower total heat demand than Technology-Optimistic based scenarios. This is because Societally Optimistic-based scenarios assume greater levels of behaviour change, such as shifting and reducing heat demand (including peak heat demand) whilst maintaining thermal comfort (e.g., in response to time-of-use tariffs). This evidence highlights the role that behavioural change has in reducing peak demand, regardless of the levels of building insulation.

Last winter NGESO launched a demand flexibility service incentivising people and businesses to reduce demand during peak periods[87] for an hour or two. Initial results suggest that across the first 5 times this service was run, energy use in peak periods was reduced by over 780MWh (equivalent to a small gas power station) with expected savings of £2.8 million to those who took part[88]. This demonstrates that behavioural change of the type shown in Societally Optimistic is achievable, although further work is required to understand if a sustained demand reduction can be achieved or only a temporary reduction as in this trial. Whilst this service is focused on changing demand patterns in return for energy bill savings, it is likely that smart EV charging and smart heating also helped facilitate this demand reduction.

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[87] The ESO's demand flexibility service, National Grid ESO (2022) https://www.nationalgrideso.com/electricity-explained/electricity-and-me/esos-demand-flexibility-service

[88] Demand Flexibility Service delivers MWs and savings, National grid ESO (2022) https://www.nationalgrideso.com/news/demand-flexibility-service-delivers-mws-and-savings

For this demand flexibility service, people were required to manually change their demand, for example by turning appliances off and then turning them back on later. Further work is needed in this area to understand how technology which could automate the shifting of demand, based on user input, could impact the level of DSR which could be achieved from behavioral change.

11.3. RECOMMENDATION

Recommendation 8: Support the accelerated uptake of Demand Side Response (DSR) solutions.

Welsh Government should work with Local Authorities and relevant public sector bodies to support the accelerated uptake of DSR options which act as flexible energy system resources. Smarter energy systems with increased potential for DSR could open up market opportunities for people in Wales and help to support networks to reduce the impact of peak energy requirements. The focus should first be on areas where Welsh Government has most influence, such as public sector buildings and social housing.

The modelling for this project has provided evidence suggesting that thermal storage and smart heating, EV charging and building retrofits are likely to be the most appropriate options for a low-cost energy system, but other options such as smart devices and LEMs should also be considered. Welsh Government should work with Local Authorities to help industry bodies support the uptake of DSR solutions by developing guidance to assist their decision-making, raising awareness with the public and working with networks to develop and demonstrate DSR solutions. With significant electrification, including heating and transport, expected to occur over the next ten to fifteen years (see Recommendation 1 and Section 4), and given the lead time on installing technologies and in particular developing markets, this guidance should be developed urgently.

12. KEY INSIGHT – ROLE OF HYDROGEN IN THE WELSH ENERGY SYSTEM

12.1. INSIGHT

Hydrogen has a role in the decarbonisation of the Welsh Energy System, particularly in decarbonising industry and shipping and providing flexible electricity generation. The overall system cost is higher in scenarios without hydrogen.

12.1.1. SUMMARY OF ANALYSIS

Hydrogen is likely to be utilised in Wales to support the transition from the 2030s. It is most likely to be cost effective in meeting industry, heavy transport (e.g., shipping) and electricity generation demands. More uncertainty remains in its use elsewhere. For example the extent of its role in supporting residential heating in some areas to alleviate peak electricity demand and for other purposes such as industry. This could be investigated further through the LAEPs, which all Welsh Local Authorities are developing with Welsh Government funding[89].

Hydrogen production in Wales could come from a range of sources (electrolysis, natural gas with CCUS, bioenergy or nuclear generation) but some hydrogen production related to electricity generation, either electrolysis or via nuclear power, would appear to result in the most cost-effective energy system. This insight focuses on the production and uses of hydrogen in the Welsh energy system. Section 14 includes insight into how hydrogen could contribute to system operation and the implications for hydrogen networks.

12.1.2. INFLUENCING FACTORS AND DEPENDENCIES

The Welsh Government has an opportunity to influence the extent of hydrogen production and consumption in Wales to be consistent with long-term decarbonisation and near-term carbon budget goals. However, a number of factors could impact deployment levels, including the safety case for hydrogen use, public acceptance, future cost of production technologies and fuel prices (natural gas for blue hydrogen production), as well as any global hydrogen market.

12.2. EVIDENCE

12.2.1. HYDROGEN'S INFLUENCE ON WALES'S TRANSITION TO NET ZERO

Hydrogen plays an important although not necessarily major role in Wales's transition to Net Zero. It provides a decarbonisation option in sectors where alternatives are limited or prohibitively expensive. The overall system cost is higher in scenarios without hydrogen. This aligns with the Climate Change Committee (CCC's) Net Zero analysis, which sees a role for hydrogen in transitioning the UK energy system to Net Zero[90].

This project has found that with no hydrogen available in the energy system, the UK Net Zero target is missed by about 8 Mt. With no hydrogen in just domestic buildings, UK Net Zero is still missed by circa 1Mt, indicating that managing and meeting peak heat demands in winter is a particular system challenge that hydrogen, thermal storage and other fuels may have a role in addressing. Sectors including industry and heavy transport include sub-sectors where alternatives

[89] Planning Policy Wales, 11th Edition, Welsh Government (2021) https://www.gov.wales/sites/default/files/publications/2021-02/planning-policy-wales-edition-11_0.pdf
[90] Net Zero: The UK's contribution to stopping global warming CCC (2019) https://www.theccc.org.uk/publication/net-zero-the-uks-contribution-to-stopping-global-warming/

to hydrogen are either technically challenging or expensive. This includes shipping, where electrified options currently appear challenging, and some industrial sectors where electrification is technically infeasible or too expensive.

The cost of producing hydrogen from different methods, the technological development of these methods, and the emissions associated with hydrogen production, all have an impact on the amount of hydrogen used in Wales and the transition to a Net Zero Welsh energy system. To highlight the impact hydrogen can have on meeting Net Zero, Figure 31 shows the difference at the UK level between the Technology-Optimistic scenario energy system cost and several sensitivity scenarios, noted in Table 2 2. Here each sensitivity assumes that one variable linked to hydrogen production or usage has evolved sub-optimally compared to Technology-Optimistic. For example, higher costs for blue hydrogen or no hybrid hydrogen heating systems available, or in the case of one sensitivity no hydrogen at all.

Sensitivity scenario name	Description
Technology-Optimistic	Technology-Optimistic Scenario. Is the reference scenario here.
Blue Capture	Blue hydrogen production is available but associated lifecycle carbon capture % (including upstream) is lower than in Technology-Optimistic, at 80% rather than 90%.
Blue Cost	Blue hydrogen production is present, but at a higher lifecycle cost.
Green Cost	Green hydrogen production is present but at variable cost points.
No H2	No hydrogen is available in this sensitivity.
No H2 Repurpose	No repurposing of the natural GDN to use hydrogen directly in domestic and service sector buildings.
No H2 BECCS	No hydrogen is produced via Bioenergy connected to carbon capture usage and storage
H2 Combi Boilers	No hydrogen hybrid heat pump systems are available. Note: Combi refers to combination boiler providing heat and hot water.

Table 2: ESME Sensitivities for Figure 31

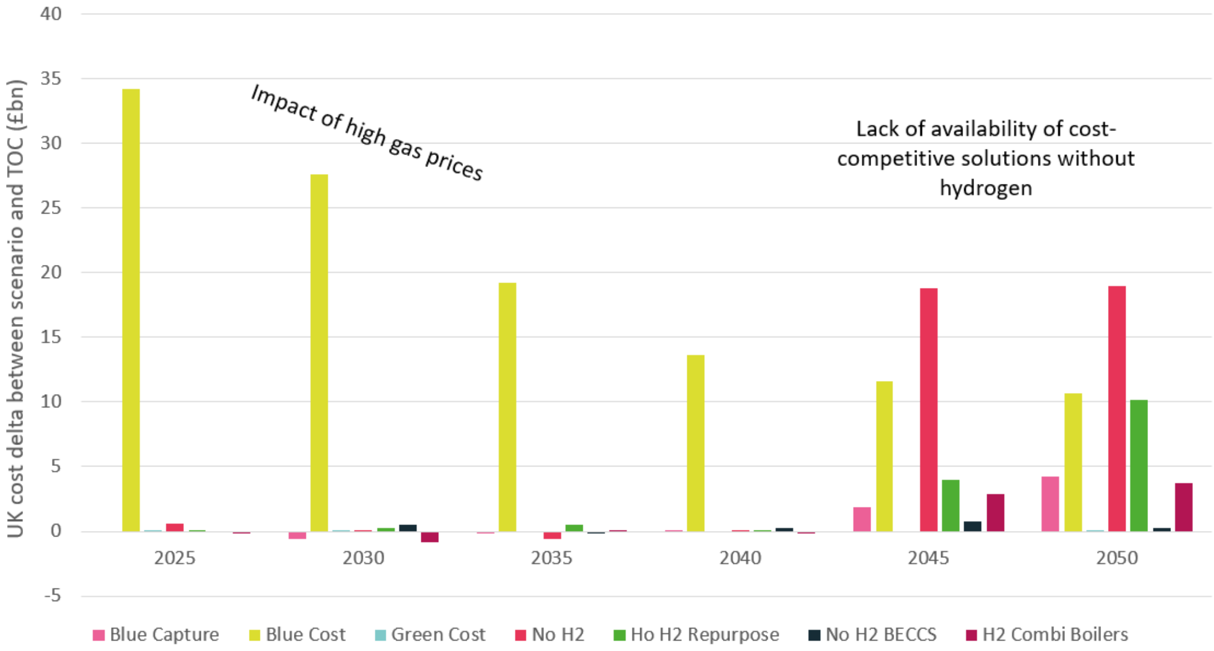


Figure 31: UK energy system cost difference compared to the TOC scenario for selected sensitivities

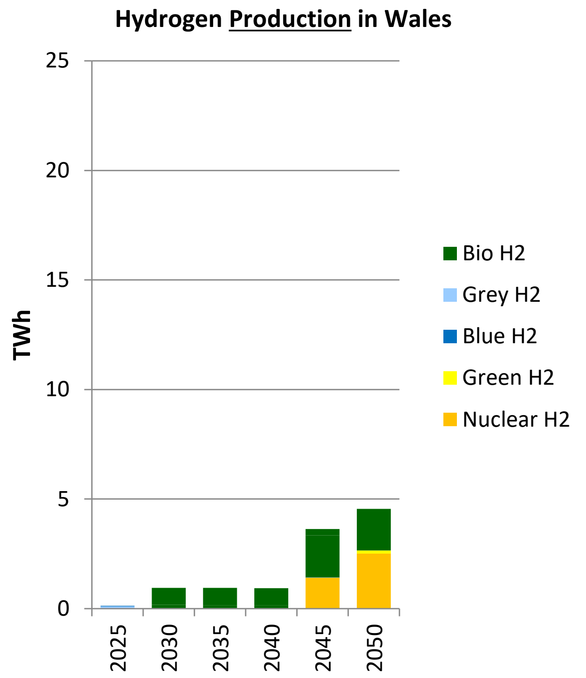
In Figure 31, all sensitivities result in increased system costs by 2050. Where natural gas remains at a sustained high level (when producing blue hydrogen) as in the 'Blue Cost' sensitivity scenario (the yellow bar) costs are highest in the intermediary years but reduce to an extent by 2050 as use of blue hydrogen (across the UK) reduces. Where there is no hydrogen, as in 'No H2' (the red bar) costs are highest from 2045 onwards as potential hydrogen production in the Welsh energy system ramps up around this time (see 14.2.2 and 14.2.3). In 'No H2', UK energy system costs are up to £19bn per year higher than in Technology-Optimistic.

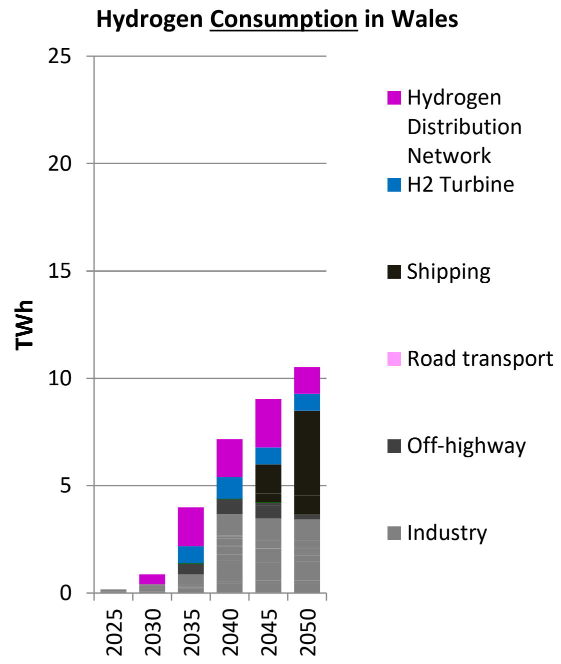
This highlights the importance of at least some hydrogen in the future Welsh (and UK) energy system to provide energy where other decarbonisation options are limited (e.g. shipping and some industry), the level of hydrogen and its use-cases is discussed in section 14.2.2 Note that whilst Wales has low levels of blue hydrogen production, under Technology-Optimistic much of the hydrogen imported from the rest of GB is blue hydrogen.

12.2.2. HYDROGEN SUPPLY

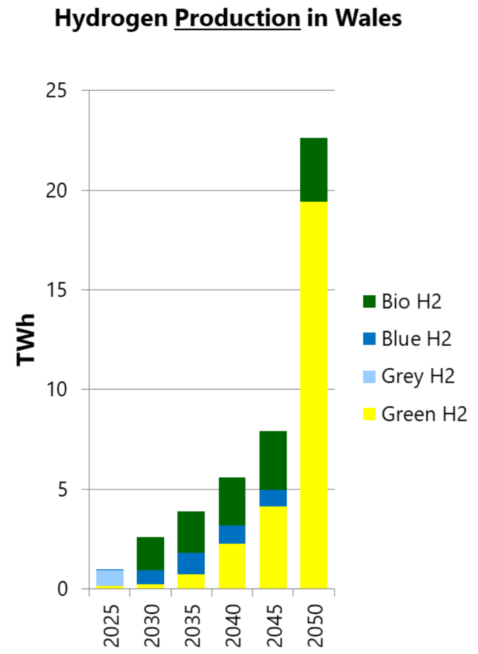
The whole energy system modelling analysis in this project highlighted that hydrogen scale up is key to decarbonisation of sectors where electrification is more challenging.

Technology-Optimistic





Societally Optimistic



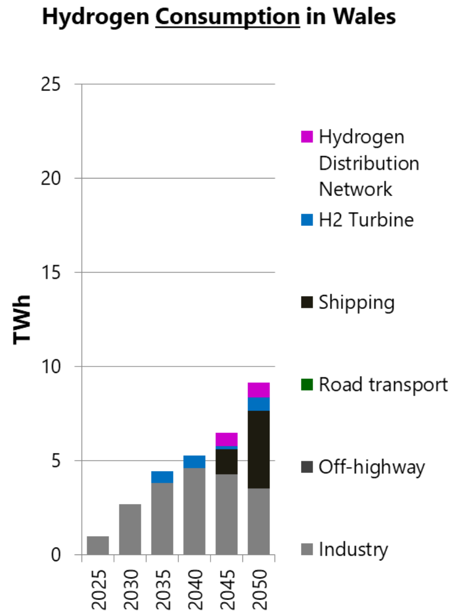


Figure 32: Hydrogen Production and Consumption in Wales

In the Technology-Optimistic scenario, by 2050 Wales is a net importer of hydrogen. Welsh hydrogen production scales up to 5TWh and consumption is at 10.5TWh for the same year. In the

Societally Optimistic scenarios production is 23TWh and consumption 9TWh so Wales is a net exporter, but at times of peak demand will need to import hydrogen to Wales from elsewhere in GB.

In all cases in Figure 32, some production of hydrogen from electricity emerges by low temperature electrolysis using wind generation. The quantity of hydrogen produced, and technology used to manufacture it depends on the wider energy systems characteristics such as:

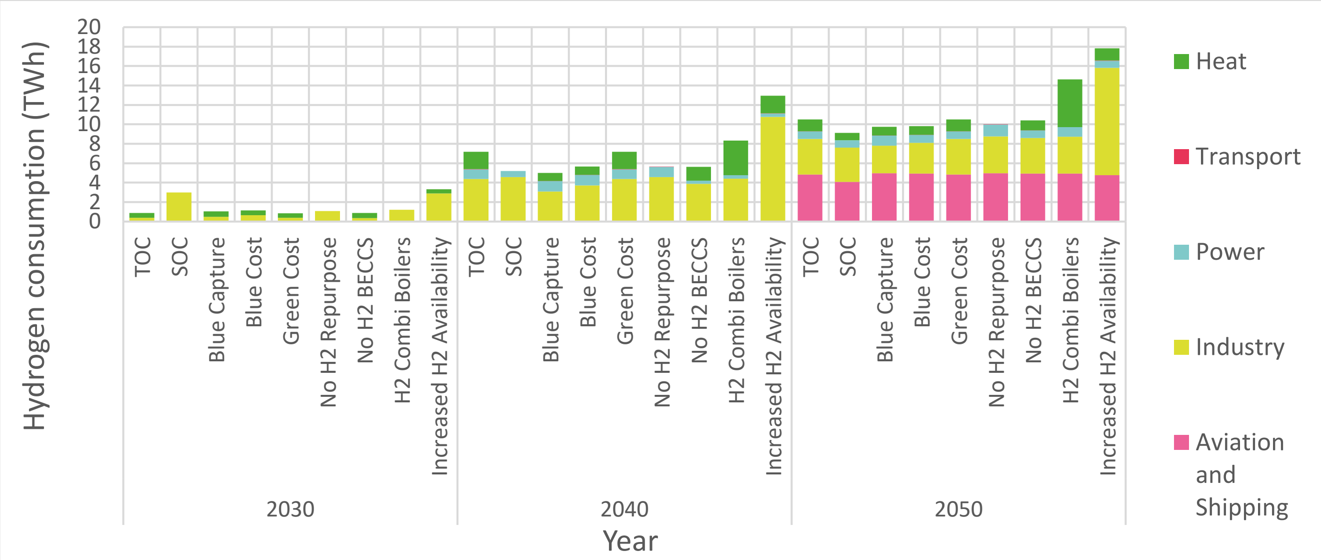
- The nature of the electricity production system, including offshore wind and availability of strategic assets such as nuclear plant.
- Technical constraints in the electricity networks.
- Market or regulator mechanisms that may influence the production of green hydrogen.
- The availability of hydrogen transmission infrastructure.
- Delivery of high carbon capture rates for blue hydrogen (and other interventions using CCS).
- Quantities of bioenergy available / acceptable in Wales, and availability of supporting Bioenergy with Carbon Capture and Storage (BECCS) technologies.
- The price of gas for blue hydrogen.

In this analysis blue hydrogen has a reduced role in Wales in each scenario. The modelling favoured locating this production technology in other areas of GB, typically near CO_2 storage sites in England[91]. In Technology-Optimistic futures, much of the hydrogen imported from the rest of GB into Wales is blue hydrogen. In Societally Optimistic futures, blue hydrogen production in Wales plays an early role, reducing to zero by 2050.

[91] This project has generally assumed that large-scale geological hydrogen storage would be in England, however it is recognised that work is underway to explore potential sites in Wales – see section 14.2.2 for more detail.

12.2.3. HYDROGEN CONSUMPTION

Figure 33 compares annual hydrogen consumption from 2030-2050 for the Technology-Optimistic and Societally Optimistic scenarios, as well as several sensitivity scenarios (see key below for descriptions).



Scenario Key

TOC – Technology-Optimistic scenario
SOC – Societally Optimistic scenario
BLUE CAPTURE – Blue H2 available but lifecycle capture % (including upstream) lower
BLUE COST – Blue H2 is present but at a higher lifecycle cost
GREEN COST – Green H2 present but at variable cost points
NO H2 Repurpose - No H2 repurposing (i.e. no H_2 in local distribution networks)
H2 COMBI BOILERS – Preferential role for hydrogen combination boilers (as opposed to hybrids)
Increased H2 Availability – Increased hydrogen usage in industry

Figure 33[92]: Annual hydrogen consumption from 2030-2050 for the Technology-Optimistic (TOC) scenario, and several sensitivity scenarios

Across all scenarios industry provides an early switch to hydrogen within specific sectors and processes. Further switches continue as hydrogen becomes available more widely, alongside demand reduction and efficiency improvements. Hydrogen demands for transportation (covering transport, and aviation and shipping in Figure 33) are dominated by aviation and shipping, with a small demand from heavy goods vehicles in some scenarios. The generally consistent demand for hydrogen for industry, and aviation and shipping highlights that there are limited alternative options for some sub-sectors in these areas. The 'Increased H2 Availability' sensitivity scenario sees an increased hydrogen demand for industry as it assumes a large industrial asset switches to hydrogen (see section 7 for more details).

There is also a generally small role for hydrogen to provide heat (usually at peak times only) and dispatchable power by 2040 (see sections 6 and 8 for more detail). Demand for hydrogen for heating does increase under the 'H2 combi boilers' sensitivity scenario, where it is assumed hydrogen boilers act in a stand-alone role rather than largely as part of a hybrid system. This was

[92] For the majority of Figures in this report we have shown five-year time-steps, due to the number of sensitivity scenarios shown in Figure 33 we've shown ten year time-steps.

generally considered to not be cost effective compared to hybrid systems under the baseline scenarios and most sensitivity scenarios. This is discussed further in section 6.

Indicative distribution of hydrogen consumption at peak times across Welsh Regions was explored for Technology-Optimistic and Societally Optimistic using the ESME Networks model. In the Technology-Optimistic scenario (Figure 34), from 2040 hydrogen is helping meet peak heat demand (although very little non-peak heat demand, as discussed in section 6). Hydrogen fuelled electricity generation plant (labelled 'H2 turbine' in Figure 34) provides dispatchable generation during peak demand times and times of low renewable output from 2035 (in South-West Wales). Hydrogen turbine generation over peak times generally reduces across the regions from 2040 to 2050 as other flexible options such as nuclear SMRs and increased DSR options become available.

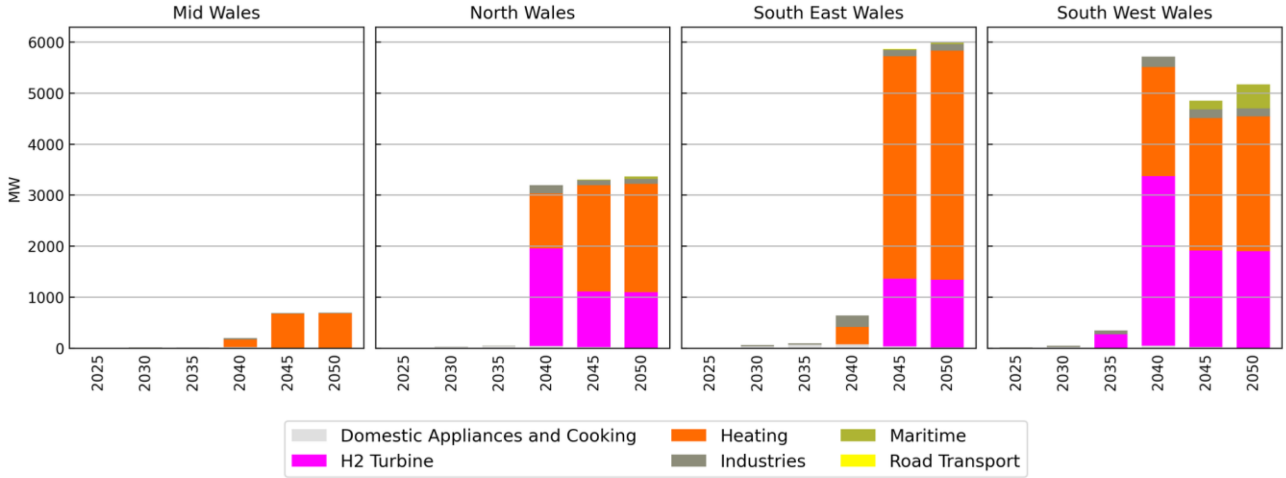


Figure 34: Peak hydrogen consumption in Wales – Technology-Optimistic scenario

In Societally Optimistic (Figure 35) hydrogen is again helping to meet peak heat demand, albeit to a lesser degree than in Technology-Optimistic, as the peak heat demand is lower due to increased behavioural change (see section 6). Once again hydrogen electricity generation plant (labelled 'H2 turbine' in Figure 35) provides dispatchable generation during peak demand times and times of low renewable output from 2035. Industry demand for hydrogen from around 2040 stays relatively constant, with other fuel switching options (including electrification and hydrogen) also helping to meet industrial demand.

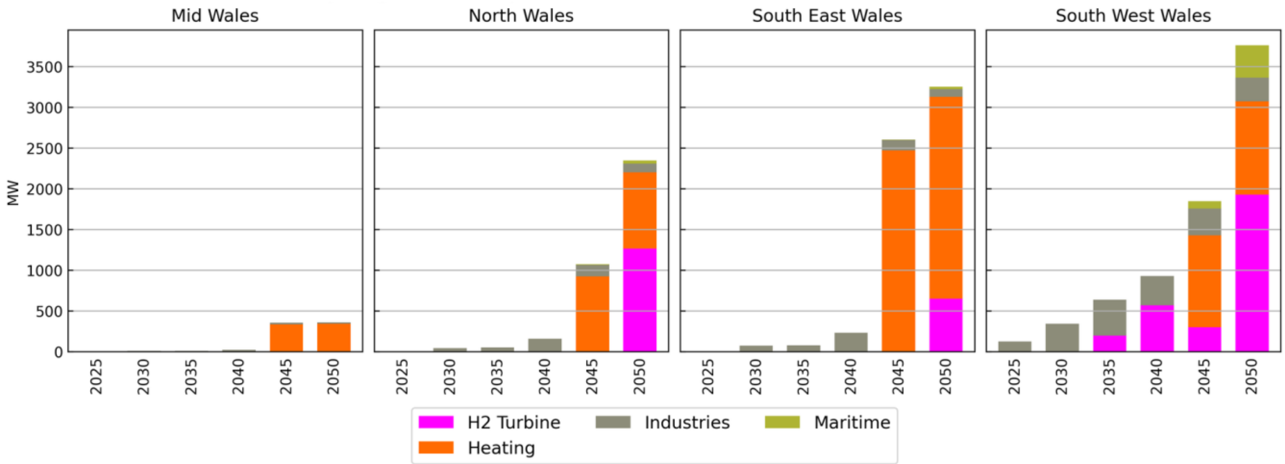


Figure 35: Peak hydrogen consumption in Wales – Societally Optimistic scenario

12.2.4. REGIONAL HYDROGEN PRODUCTION

The location of hydrogen production in Wales varies across the scenarios. Practically, siting of these facilities will be highly dependent on local factors and the input assumptions to the model. However, some useful early strategic insights were gained into different distribution of hydrogen production locations in Wales on the energy systems explored[93].

Figure 36 shows the installed hydrogen production capacity in Wales by region in the Technology-Optimistic scenario. Hydrogen produced from biomass with CCS is deployed first as it is a source of negative emissions. Biomass is being used for hydrogen production rather than for producing electricity or heat due to the other decarbonisation options available for those uses.

There is only very limited uptake of electrolysis in the Technology-Optimistic scenario, and only in 2050, due to the cost of the additional generation capacity this requires. Electrolysis could present an opportunity in earlier years as an alternative to building electricity transmission networks, transporting hydrogen instead. However, under this scenario this comes at a higher system cost. Hydrogen is produced from nuclear cogeneration, assumed to be at Wylfa nuclear power plant. Hydrogen production from biomass is based around Connah's Quay and Deeside.

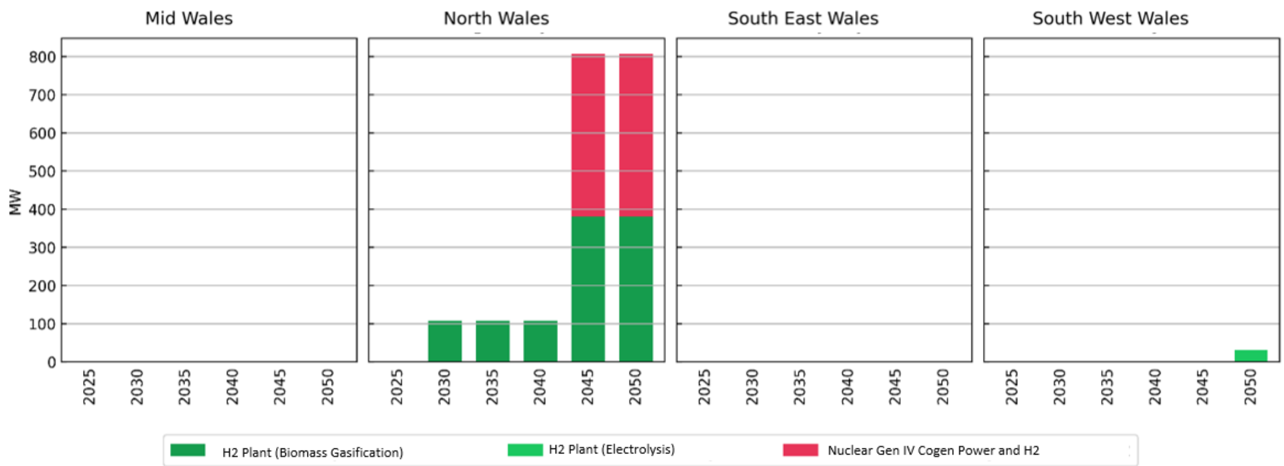


Figure 36: Hydrogen Production Capacity for onshore Wales – Technology-Optimistic

In the Societally Optimistic scenario Wales is a net exporter, but at times of peak demand will need to import hydrogen. Due to lower capture rates for CCS in this scenario, electrolysis is favoured for hydrogen production. Figure 37 shows that some hydrogen production from electrolysis is located in the South-West at Pembroke near to possible landing sites for offshore wind. In North Wales hydrogen production is again based around Connah's Quay and Deeside, with a combination of electrolysis and hydrogen from biomass, as well as a small amount of blue hydrogen[94]. Although not modelled, this is linked to assumptions based on the availability of hydrogen infrastructure in the area provided by the HyNet project.

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93 Please note that the SWIC Cluster Plan has looked at local factors influencing hydrogen production and demand. Whilst those results are distinct and different, they do provide some overlapping conclusions.

94 Note that whilst a small amount of H_2 Plant (ATR with CCS) (i.e. blue hydrogen) capacity remains until 2050, it has largely stopped producing by 2050 and is there to support energy security only, and so is consistent with hydrogen production shown in Figure 32.

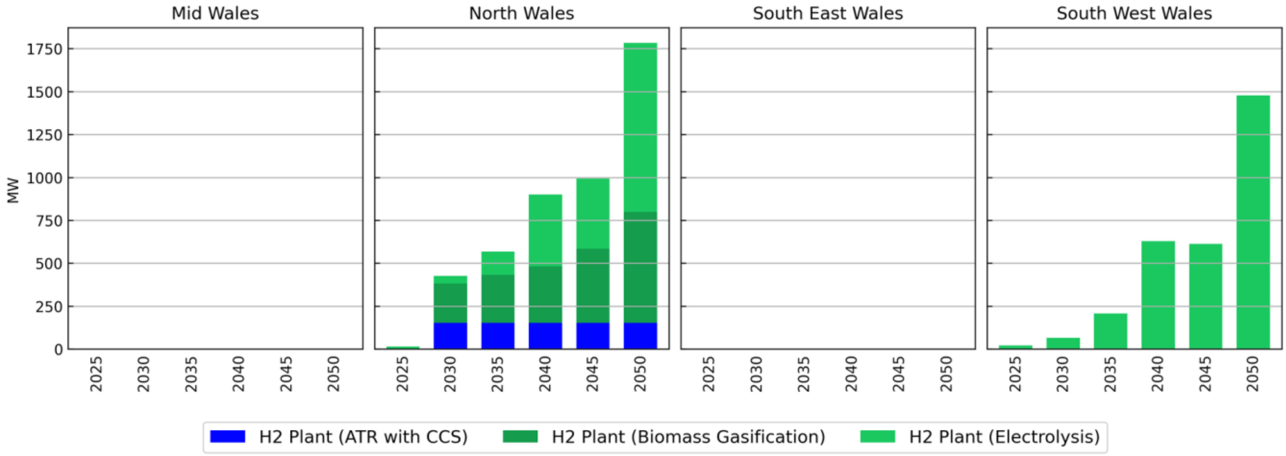

Figure 37: Hydrogen Production Capacity for onshore Wales – Societally Optimistic

12.3. RECOMMENDATION

Recommendation 9: Assess the benefits and risks of different hydrogen production technologies, at specific locations, starting with green hydrogen.

The need for hydrogen in a cost-effective Welsh energy system is likely to ramp up, with annual Welsh hydrogen consumption in 2030 at 0.9TWh and 3TWh for Technology-Optimistic and Societally Optimistic respectively, and 10.5TWh and 9TWh in 2050 (with a further 14TWh being exported to the rest of GB in Societally Optimistic). By 2050 the role of hydrogen within Wales is similar across both scenarios with the main uses being for shipping and industrial processes. However, by 2050, the methods used to produce hydrogen and the total amounts produced (once exports are accounted for) varied across the scenarios. This can result in significantly different impacts on the energy system with electricity demand heavily impacted by levels of electrolysis deployment.

Some green hydrogen production from electrolysis was present in both baseline scenarios by 2050. However, the scale of electrolysis suggested varied considerably (from only 140GWh in Technology-Optimistic to 19TWh in Societally-Optimistic by 2050). Additionally, the use of other technologies to produce hydrogen such as steam methane reformation (i.e., blue hydrogen) or hydrogen supported by nuclear generation also varied between scenarios. In reality, a number of local conditions and decisions, and UK Government decisions will determine whether and where these technologies are deployed. Therefore, Welsh Government should explore technology options further to understand the drivers, as well as potential benefits and risks for supporting investment decisions related to all hydrogen production technologies, at specific locations. Timeframes for this should recognise the UK target of 10GW of hydrogen production by 2030[95].

[95] British energy security strategy, UK Gov (2022) https://www.gov.uk/government/publications/british-energy-security-strategy/british-energy-security-strategy

13. KEY INSIGHT – STORAGE AND FLEXIBILITY

13.1. INSIGHT

The Welsh energy system will require additional short and long duration flexibility to balance supply and demand as more renewable generation is deployed. This could include demand-side response, partially facilitated by thermal energy storage; electricity storage such as pumped hydro and batteries; and hydrogen storage, enabled by a transmission network to the rest of GB.

The Welsh energy network is greatly enhanced, economically and in terms of reliability, by having strong interconnectivity with the GB energy system.

13.1.1. SUMMARY OF ANALYSIS

Increased renewable energy deployment requires new types of flexibility to balance supply and demand. This includes technologies operating on timescales from minutes and hours to several days and across seasons. This modelling insight was confirmed by stakeholders.

Flexibility could come from a combination of solutions:

- Demand Side Response;
- Increased imports/exports from the wider GB network;
- Storage technologies such as batteries and pumped hydro storage, including the existing Dinorwig and Ffestiniog stations; and
- Hydrogen.

GB electricity and gas networks can also provide flexibility, allowing energy to be transferred relatively easily across regions and countries. Whilst network constraints must be managed, this network flexibility should be utilised alongside other solutions. For example, storage or other sources of flexibility across the GB network can be used to provide flexibility to Wales when required. Equally, Wales has the opportunity to provide flexibility to the rest of GB via, for example, electrolysis that could help to consume otherwise curtailed renewable generation from across GB. Utilising this network flexibility could reduce system costs and provide economic opportunities for Wales (e.g. enabling increased connection of renewable generation, flexibility assets in Wales selling flexibility services to the rest of GB).

13.1.2. INFLUENCING FACTORS AND DEPENDENCIES

The modelling analysis in this project considered the levels of electricity storage required out to 2050 for the baseline scenarios and several sensitivity scenarios. ESC's analysis using ESME suggests that electricity storage requirements can be minimised through effective DSR and a flexible hydrogen system. However, ESME is a strategic whole system model and has a limited view of the changing operational requirements for energy storage and flexibility over short timeframes. ESME underestimates the need for additional storage and its very likely that additional storage will be appropriate to help manage local, regional and national issues. Studies with a more operational focus could project higher requirements for electricity storage. Stakeholder engagement supported this view.

13.2. EVIDENCE

13.2.1. ELECTRICAL STORAGE

Figure 38 shows dedicated electrical storage volume (GWh) from 2030 to 2050 for Technology-Optimistic, Societally Optimistic and four sensitivity scenarios, as detailed in the legend. The existing pumped hydro storage in Wales (~10GWh) will continue to be used out to 2050. ESC's modelling suggests additional strategic electricity storage beyond this is not cost-effective. This is not because new flexibility isn't needed but rather that this flexibility is provided by other sources, across vectors, such as DSR (including battery storage in the form of smart EV charging, as well as smart heating with thermal storage – see section 11) and hydrogen. As discussed above, it is likely that this analysis underestimates the need for electricity storage.

In future pathways where these alternative sources of flexibility are not available, additional electricity storage is required. This can be seen most clearly in Figure 38, in the sensitivity scenario 'TOC Adjusted Electrification no H2'. Here there is no hydrogen in the distribution network, and so no hydrogen for domestic heating and with a much larger rollout of heat pumps. The combination of no hydrogen and increased electrification of heat (via heat pumps) increases the need for flexibility to reduce peak electricity demands. This in turn results in increased strategic electricity storage with around 18GWh of pumped hydro and 7GWh of battery storage by 2050.

Whilst the increased need for electricity storage is most noticeable in this future pathway, other pathways with reduced flexibility also see an increased need for additional electricity storage, mainly in the form of batteries. For example, 'SOC Low Heat Storage', which restricts thermal storage and therefore smart heating, and 'SOC Low EV Smart Charging', which restricts EV smart charging, both see deployment of batteries by 2050.

Engagement with stakeholders supported the view that additional flexibility would be needed in the future, including electricity storage. Electricity storage options suggested included, pumped hydro storage; lithium-ion batteries; and compressed and liquid air storage. Ensuring a positive planning and regulatory environment for additional electricity storage that may be required in the future in Wales will be beneficial.

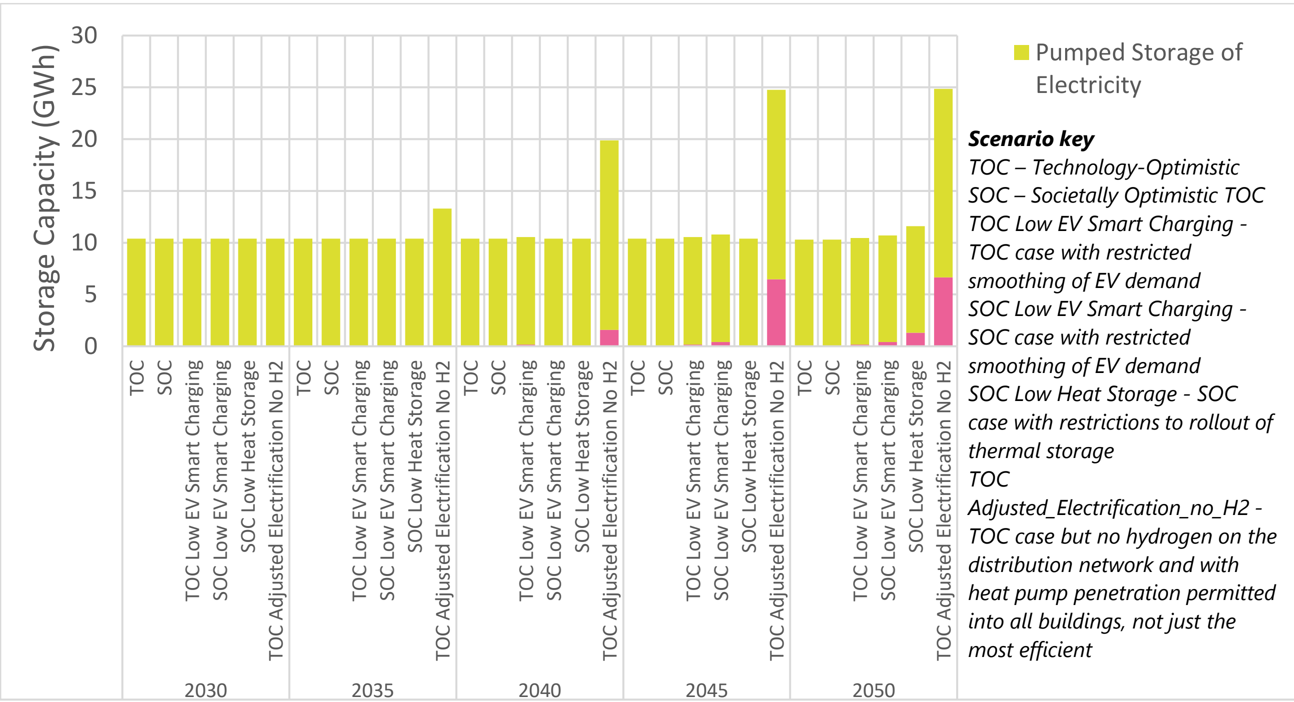

Figure 38: Electric storage capacity for Technology-Optimistic, Societally Optimistic and selected sensitivity scenarios

13.2.2. HYDROGEN STORAGE

Hydrogen storage could provide long duration flexibility to the energy system in Wales by 2040 (e.g., through the use of hydrogen turbines). If produced by electrolysis, hydrogen could help to

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use power where generators would otherwise be curtailed as well as mitigating electricity network constraints. Whilst Wales could be a net producer or consumer of hydrogen (depending on model assumptions, see section 12), in both cases it needs hydrogen storage in England to support with cold windless periods which will require a hydrogen transmission network. This highlights the flexibility benefits an energy network can provide.

It is currently assumed that Wales does not have suitable geology for large scale underground hydrogen storage such as salt caverns[96], and above-ground hydrogen storage was excluded on cost grounds. However, research is being undertaken to assess the potential for salt cavern development for hydrogen storage in and near to South Wales[97]. This could make Wales less reliant on hydrogen storage in other parts of GB.

13.3. RECOMMENDATION

Recommendation 10: Encourage greater use of flexibility in the energy system in Wales to more efficiently manage energy demand and supply.

Flexibility within Wales should be promoted immediately and sustained throughout the transition, as it has the potential to alleviate network constraints, provide stability services and balance supply and demand. This could include DSR (i.e., EV smart charging; smart heating supported by thermal storage), existing pumped hydro storage, and new installations of storage technologies such as batteries, liquid air energy storage, and compressed air energy storage. The flexibility GB electricity and gas networks can provide should also be utilised (e.g., utilising hydrogen storage, or other forms of storage located across GB).

Welsh Government should work with developers and providers to support flexibility and storage projects, which should include continuing to ensure a positive planning environment for projects on the distribution network, where planning is a devolved matter, and working with Local Authorities to support storage and flexibility in domestic properties (see Recommendation 8).

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[96] Salt Cavern Appraisal for Hydrogen Power Generation Systems, Energy Technologies Institute https://www.eti.co.uk/programmes/carbon-capture-storage/salt-caverns

[97] Potential for Salt cavern storage of hydrogen in and near South Wales, Wales and West Utilities (2022) https://smarter.energynetworks.org/projects/nia_wwu_2_10/

14. KEY INSIGHT – HYDROGEN TRANSMISSION

14.1. INSIGHT

Hydrogen transmission[98] infrastructure could be needed in South-West Wales from the early 2030s. Due to design, planning and construction lead times, decisions on the needs assessment will need to be made in the near-term for this to be achieved.

In North Wales, the potential deployment of hydrogen turbines, and nuclear power in combination with a hydrogen transmission network in North-West England, could make the area attractive for hydrogen production, also prompting a need for hydrogen transmission.

14.1.1. SUMMARY OF ANALYSIS

Hydrogen is required in several sectors in specific localised areas throughout Wales, in a cost-effective Net Zero energy system. Sectors utilising hydrogen include industry and power in both the North and South, plus heavy transport and mixed industry throughout the country. Hydrogen network infrastructure is likely to be required to some extent throughout Wales, especially South-West Wales and North Wales.

In South-West Wales the primary drivers for gaseous transmission infrastructure are the supply to power generation and industry, and access to storage facilities in England to support the Welsh energy system during cold, windless periods. Hydrogen produced in North Wales could link to hydrogen infrastructure in North-West England via a transmission network.

14.1.2. INFLUENCING FACTORS AND DEPENDENCIES

The adoption and role of hydrogen is still in its very early stages, with high levels of uncertainty about its role in the energy system (see section 14). This adds additional uncertainty to key technical hydrogen transmission questions, such as whether to repurpose existing gas transmission or lay new pipes.

Where to locate hydrogen production facilities and unpack hydrogen carriers is influenced by multiple factors. For Wales, global hydrogen trade, electricity generation and electricity transmission network developments could make additional sites attractive. For example, North-West Wales could host additional electricity generation (e.g. nuclear generation at Wylfa, Combined Cycle Gas Turbine (CCGT) at Deeside and/or Connahs Quay replaced with hydrogen turbines) and link up with offshore wind generation. The additional electricity transmission infrastructure this would bring combined with existing port infrastructure, allowing access to a global hydrogen market, may mean the area could be attractive for hydrogen production facilities. In this case there may be a need for additional hydrogen transmission infrastructure connecting to the North-West of England.

Increased certainty in the availability of hydrogen infrastructure (both hydrogen production and hydrogen transmission infrastructure) in Wales would reduce uncertainty for potential Welsh use-cases of hydrogen (e.g. for industry, power generation and potentially some heat). This is because the levels of hydrogen available for these use-cases would be more certain.

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[98] The term transmission is used here to cover local or national networks with similar technical characteristics to that seen in natural gas networks. Specific technical details would be subject to needs case and strategic technical analysis.

14.2. EVIDENCE

14.2.1. HYDROGEN NETWORK NEEDS DEPEND ON ITS ROLE

The specific hydrogen network needs will depend on the role of hydrogen in the energy system. Using the Technology-Optimistic scenario as a baseline, a sensitivity was explored where local hydrogen distribution networks were not available.

Figure 39 and Figure 40 below show peak evening gaseous (i.e., hydrogen and natural gas) consumption by use and vector (H for Hydrogen, G for natural gas). The top chart shows Technology-Optimistic which includes hydrogen in the distribution network while the bottom chart shows a sensitivity with no hydrogen in the local distribution network, and therefore no hydrogen for heat. In this case some gas is still consumed for heating which means a gas distribution network is retained. Note this sensitivity is not consistent with a fully Net Zero system, with around 1Mt of CO2 emissions remaining in the system by 2050.

By 2040 hydrogen for power makes up a significant proportion of peak gaseous demand in Figure 39 and especially Figure 40 where there is no hydrogen for heat. Hydrogen demand for industry is also present. Both use-cases sit at transmission level, suggesting a hydrogen transmission network will be required.

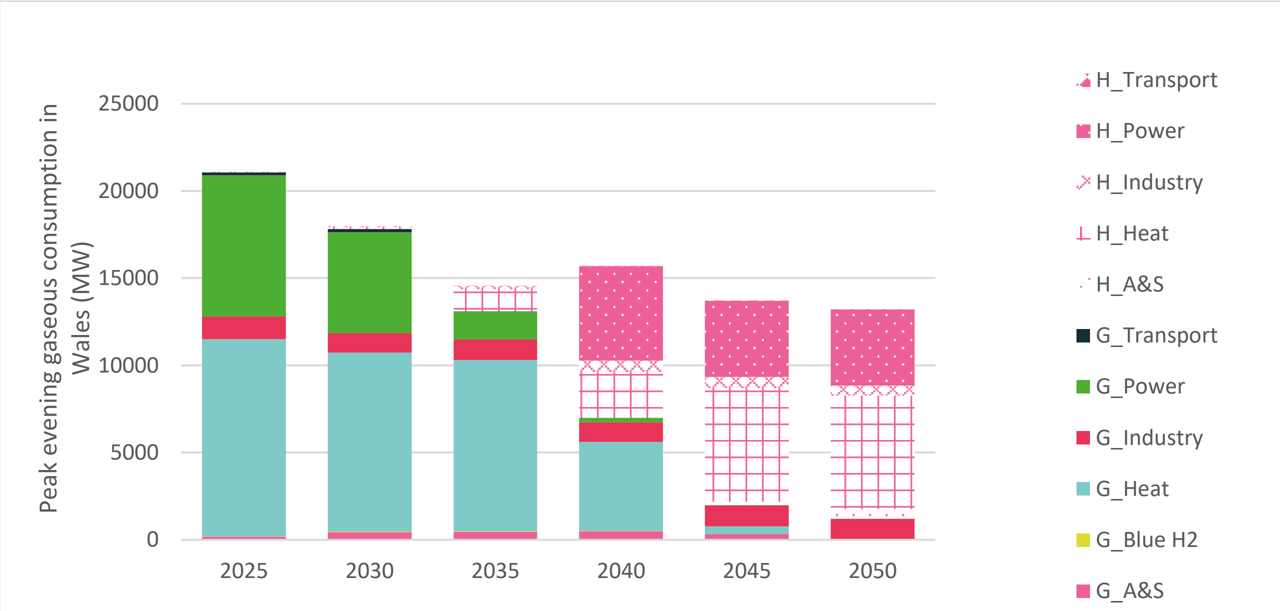

Figure 39: Technology-Optimistic scenario illustrating gaseous peak consumption in MW, showing both natural gas and H_2 consumption. H_2 consumption is relatively large as it is used for the decarbonisation of heat

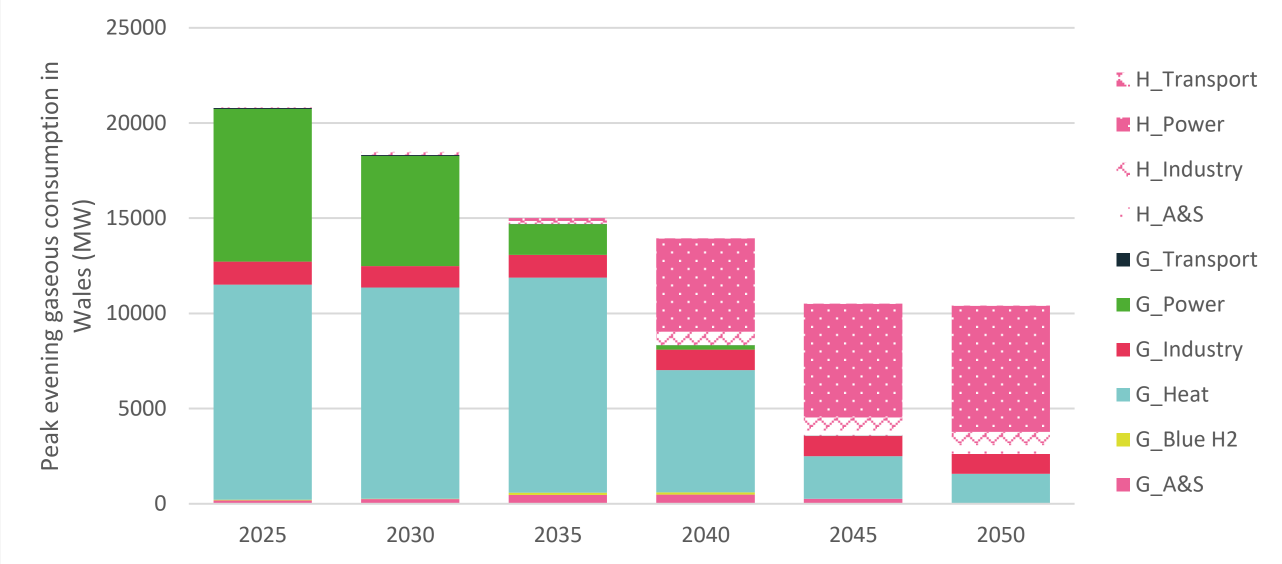

Figure 40: No H2 Repurpose scenario – a sensitivity conducted where H_2 was removed in local distribution networks, which resulted in minimal H_2 usage for heat but increasing H_2 use for power production

14.2.2. LOCATION OF TRANSMISSION PIPELINES

Wales has existing transmission pipelines for natural gas, located on an East to West axis in the south and the north of the country. Mid-Wales is served by a North-East to South-East pipeline from the Wrexham area. Hydrogen transmission pipelines are likely to use either re-purposed natural gas lines or require the construction of hydrogen specific assets.

Initial routes of pipelines are driven by the need to connect demands with supply. Milford Haven was identified as an early hydrogen supply point during stakeholder engagement (Figure 41). With large power generation and industrial demands also in the South-West of Wales driving demand, if there is no local hydrogen storage, there would be a need for a pipeline to English storage for flexibility[99]. Two industry projects have provided plans to provide this infrastructure: the Wales and West Utilities HyLine Cymru[100] and the National Gas Transmission (NGT) Project Union[101].

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[99] This project has generally assumed that large-scale geological hydrogen storage would be in England, however it is recognised that work is underway to explore potential sites in Wales

[100] Major hydrogen pipeline planned to decarbonise Welsh industry, Wales & West Utilities (2022) https://www.wwutilities.co.uk/news-and-blog/major-hydrogen-pipeline-planned-to-decarbonise-welsh-industry/

[101] Launch Report. National Gas (2022) https://www.nationalgas.com/document/139641/download

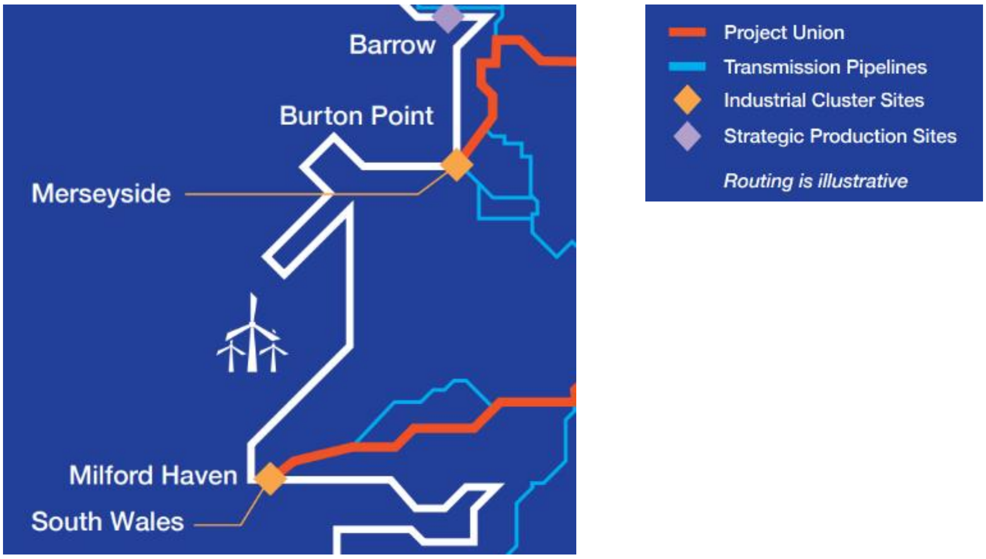

Figure 41: Source National Gas, 2023[102]

In North Wales the need for hydrogen transmission is more uncertain. Deeside was identified as an early hydrogen supply point and with HyNet in the region this could be an early location for hydrogen transmission. This could be further supported if there was nuclear based hydrogen production at Wylfa nuclear power plant (as in the case of Technology-Optimistic where a nuclear SMR at Wylfa cogenerates hydrogen). An extract from HyNet project information is provided in Figure 42.

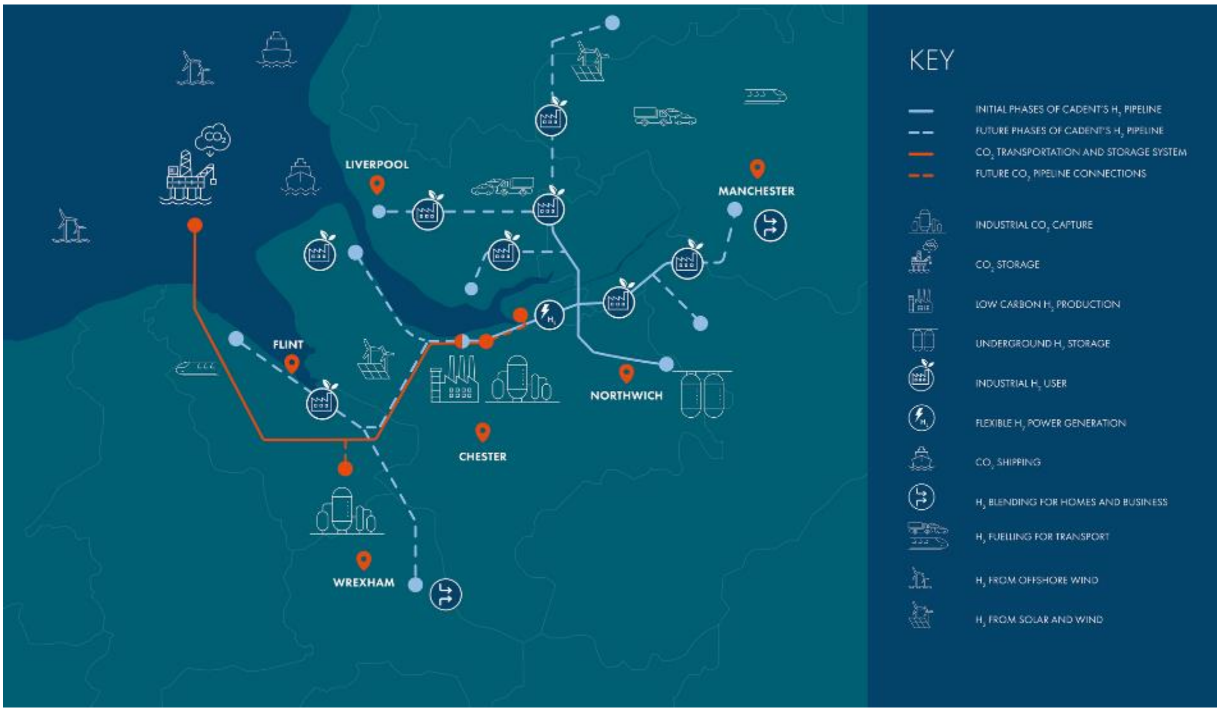

Figure 42: Overview of HyNet Project, 2023[103]

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[102] Launch Report, National Gas (2022) https://www.nationalgas.com/document/139641/download
[103] What is Hynet?, Hynet https://hynet.co.uk/about/

14.2.3. NATURAL GAS CONSUMPTION CHANGE

The deployment of hydrogen transmission networks in Wales may reuse existing natural gas infrastructure, if repurposed. This approach would mean that repurposed gas network would not be available to transport natural gas. Understanding how gas consumption changes will help to identify when natural gas transmission infrastructure could be repurposed. The change in natural gas peak consumption was explored for the Welsh regions using ESC's ESME Networks model.

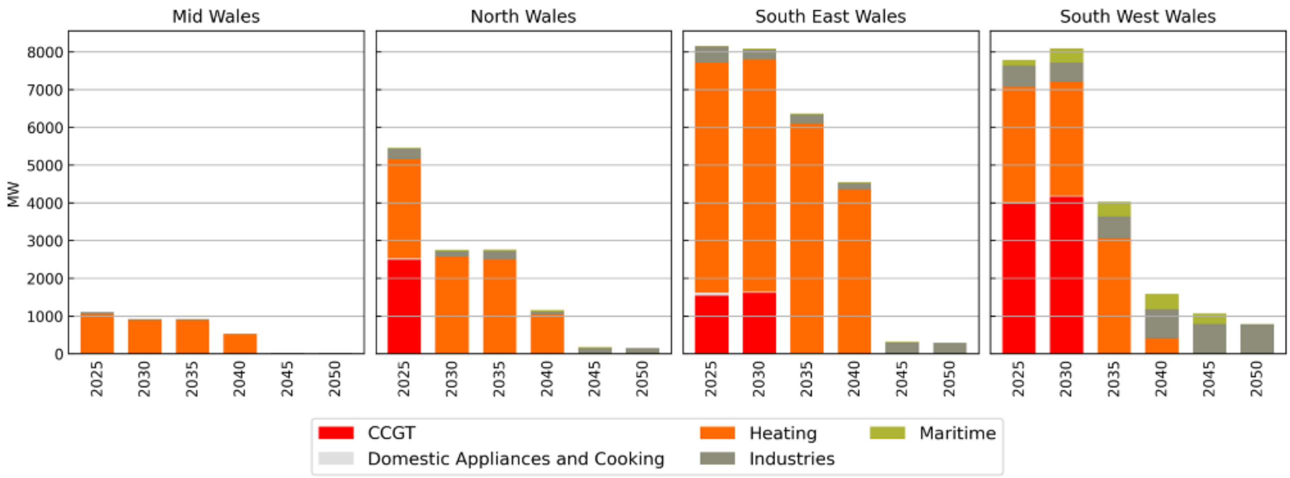

Figure 43: Natural gas peak consumption for Wales – Technology-Optimistic

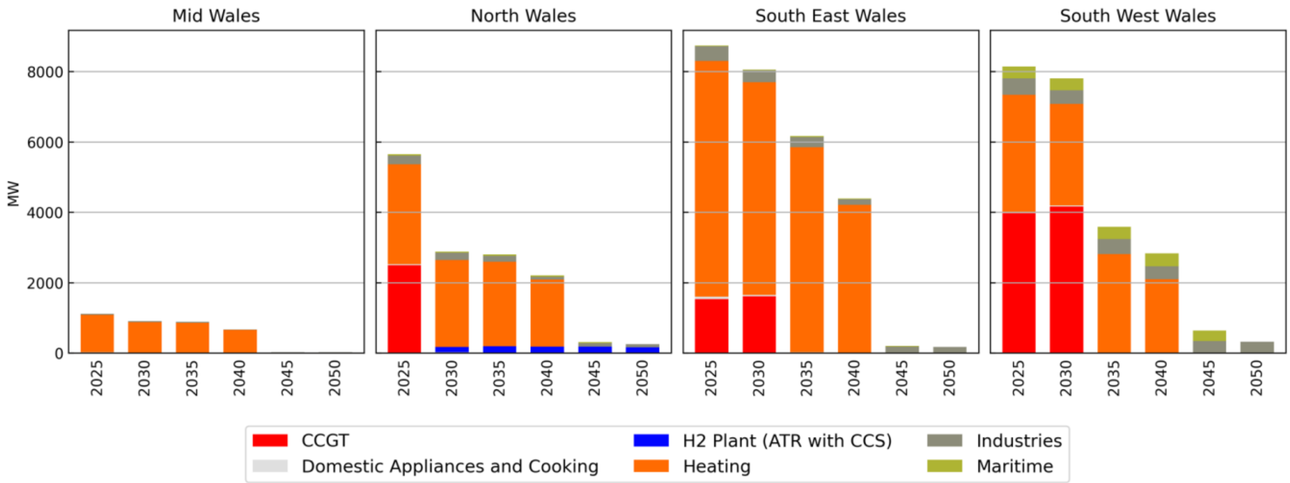

Figure 44: Natural gas peak consumption for Wales – Societally Optimistic

Figure 43 and Figure 44 show natural gas peak consumption for the regions in the Technology-Optimistic and Societally Optimistic scenarios respectively. In both scenarios power generation using natural gas-powered CCGT is phased out by 2035, while natural gas for heating is reducing from 2035 and phased out by 2045. These trends align with the UK Government's targets for a zero-carbon power system by 2035 and to install no new gas boilers from 2035.

Some gas demand for industry remains in both scenarios out to 2050, combined with CCS. However, the lower assumed carbon capture rate in Societally Optimistic means the amount is smaller. In Technology-Optimistic there is no demand for gas for hydrogen production in Wales but some of the hydrogen imported from England is produced using natural gas. In Societally optimistic there is a very small amount of gas demand for hydrogen production in North Wales from 2030 to 2045, but most hydrogen production is via electrolysis.

The significant reduction in gas demand post 2035 suggests that from this point onwards there may be potential to repurpose some gas infrastructure, especially from 2045 when gas consumption has become particularly low. However, detailed localised analysis will be required to understand when and where specific parts of the gas network could be repurposed, or if new hydrogen infrastructure would be more appropriate.

Stakeholder engagement highlighted that across Europe there is an ambition to decarbonise more quickly for reasons of energy security. This is relevant to Wales as the largest natural gas pipeline in the UK connects Milford Haven to the NTS in Gloucestershire. One of the main reasons the pipeline is needed is to connect LNG imports to the UK and onwards to European markets via gas interconnectors. If the European market for natural gas were to reduce, this could release capacity from the natural gas transmission network in Wales earlier than expected.

Whether natural gas users switch to hydrogen is likely to be highly dependent on the geographical region. From a gaseous network perspective, switches from natural gas to hydrogen are likely to be demand driven, with large industrial customers leading.

14.3. RECOMMENDATION

Recommendation 11: Work with network operators to assess the benefits of a hydrogen transmission network in Wales, accounting for key uncertainties and wider economic benefits.

The need for hydrogen in a cost-effective Welsh energy system could ramp up through the 2030s and prompt the need for a transmission network, most likely in South-West Wales and potentially in North Wales. Hydrogen transmission network infrastructure in Wales could provide benefits including supporting the use of hydrogen for decarbonisation and creating skilled job opportunities. However, there are uncertainties which present risks to hydrogen infrastructure, such as the safety case, public acceptance, hydrogen's role (although hydrogen for shipping and industry are the main use cases in both baseline scenarios by 2050), and location of hydrogen demand and production centres.

Welsh Government should work with the networks and industry, building on existing analysis, to quantify the potential benefits, costs and impacts a hydrogen transmission network may bring to the Welsh economy, accounting for the key uncertainties. This will support Welsh Government in arriving at a view on hydrogen transmission networks. Whilst this analysis suggests that the role of hydrogen, and therefore the possible need for a transmission network, in the Welsh energy system really ramps up from 2035 to 2040 onwards, the long lead time on infrastructure development suggests this analysis needs to happen relatively quickly.

15. KEY INSIGHT – A NEW FUNCTION: WELSH ENERGY SYSTEM COORDINATION

15.1. INSIGHT

A new function is needed to represent Welsh aspirations, coordinating with network operators, the FSO and other relevant stakeholders, on investment decisions and future planning including the Centralised Strategic Network Plan.

15.1.1. SUMMARY OF ANALYSIS

Currently networks carry out planning based on scenarios (Future Energy Scenarios (FES) for transmission and Distribution Future Energy Scenarios (DFES) for distribution). This is undertaken separately for gas and electricity networks. It is very challenging for networks to collate the various ambitions at different levels of government (i.e., national, regional, local), industry and wider business and civic society, to inform this work.

Welsh Government is leading a programme of energy planning by funding all Welsh Local Authorities to produce a Local Area Energy Plan (LAEP).

In many cases, stakeholders do not have a clear view of their future requirements and the implications for the grid. Separate development of plans misses a major opportunity to consider the interplay between the different networks and identify the least cost plans that meet the needs of stakeholders and deliver Net Zero targets. Planning the optimal network for Wales requires a strong knowledge of the country and strong technical knowledge of networks.

A new function could facilitate the coordination of LAEPs, and provide input into network plans by engaging with the FSO, Distribution System Operators (DSOs), Gas Distribution Network (GDN) and in the future, the proposed RSP[104], helping to unlock local action. This is a role that the RSPs could eventually fill, but they are unlikely to be operational for several years, so a well-designed function could fill an important role in the near-term.

15.1.2. INFLUENCING FACTORS AND DEPENDENCIES

This function would facilitate opportunities for Welsh Government and Local Authorities, and potentially other organisations representing Welsh interests, to work with DNOs, GDNs and Local Authorities, acting as a convener in the near-term to support a whole-system approach to the alignment and aggregation of LAEPs and provide a valuable input into network plans. This work would also allow investigation of differences where alignment is not possible.

This process would allow quicker and more confident energy infrastructure decisions, aligned with Welsh regional and local plans. There may also be additional scope for this function, for example, it could also provide an advisory role to the Welsh Government on the energy system transition landscape.

15.2. EVIDENCE

The need for coordinated whole system network planning and anticipatory investment in the energy networks was clear from the evidence review and stakeholder engagement. In the absence of a fully formed FSO and key decisions on the RSP design, there are institutional gaps and

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[104] Consultation: Future of local energy institutions and governance, Ofgem (2023) https://www.ofgem.gov.uk/publications/consultation-future-local-energy-institutions-and-governance

uncertainty around the most suitable organisations to perform some energy functions. There is also a lack of coordination between some sub-national energy actors[105]. These all act as barriers to whole system, strategic network planning and investment. To make sure networks can be enablers of Net Zero there is a requirement for a flexible, strategic and judgement-based approach to enable whole systems investment decisions.

15.3. RECOMMENDATION

Recommendation 12: Explore the creation of an independent function focusing on facilitating Welsh whole system network coordination and investment decisions.

Welsh Government should explore the creation of a new function to represent Welsh aspirations for Wales in the near-term, with the required expertise around whole energy system and network transition. This could facilitate the coordination of LAEPs and engage with the FSO, DSOs, and GDNs in the absence of the RSP[106]. There is a gap in the current institutional and regulatory landscape to unlock local decision-making – this is something that the RSPs could eventually fill, but they are unlikely to be operational for several years, so a well-designed function could fill an important role in the near-term, and potentially longer term for some activities.

This should be set up with a phased approach to expediate its establishment. The function should operate independently from the networks and represent Welsh aspirations and needs. Through this function, Welsh Government and Local Authorities should find opportunities to work with DNOs and GDNs, acting as a Local Authority convener and arbiter in the near-term to support the alignment and aggregation of LAEPs and provide a valuable input into network plans. This work would also allow investigation of differences where alignment is not possible. This process of alignment and aggregation should also help to provide investors with confidence to invest in the assets that LAEPs identify are required. The function could also provide an advisory role to the Welsh Government on the energy system transition landscape.

[105] Call for Input: Future of local energy institutions and governance, Ofgem (2022) https://www.ofgem.gov.uk/publications/call-input-future-local-energy-institutions-and-governance
[106] Consultation: Future of local energy institutions and governance, Ofgem (2023) https://www.ofgem.gov.uk/publications/consultation-future-local-energy-institutions-and-governance

16. NETWORK IMPLICATIONS

The development of the key insights and recommendations highlighted important implications for the energy networks. These are listed below and are factors that network companies should be considering in their future network planning work.

Network Implication 1: Increases in peak electricity demand will create a need for electricity distribution network reinforcement.

The whole system analysis using ESME, carried out in this project, suggests significant increases in peak electricity demand which will require significant electricity network reinforcement, particularly on the distribution network. To provide more clarity on the extent and location of the required reinforcement, increased certainty around the location and composition of generation and end-use demands and future peak network demands is needed. Two areas with significant uncertainty and materiality for electricity networks are how much peak heat demand will be met by electrified options; and how much hydrogen will be produced by electrolysis, which could have a large impact on peak electricity demand. The former is likely to have a more significant impact in the short term as electrified heat options and electric vehicles continue to see increased deployment, whilst the latter could begin to have an impact in the 2030s where there is potential for hydrogen production and demand to ramp up considerably.

Whilst electricity network operators have plans to reinforce in the near-term, through the RIIO-ED2 price control periods[107], Ofgem's ASTI process and long-term development statements (LTDS)[108] [109], there is still considerable uncertainty around estimates of future peak demand out to 2030 and beyond, which impacts networks' ability to deliver reinforcements. The shorter visibility on some demand loads (e.g., EVs, heat pumps) creates challenges for DNOs, but the RIIO-2 uncertainty mechanisms provide an opportunity to respond, as these uncertainties reduce. Improved understanding of likely future peak demands will help to inform the requirement for network reinforcement, which will in turn contribute to enabling networks to invest ahead of need. The uncertainty mechanisms should also be utilised to tackle the current and future challenge of providing additional network connections, both for new distributed generation and additional demand. The future price control structure, currently being consulted on by Ofgem (post RIIO-2, and beyond) should be designed to provide further means to deliver further, timely, anticipatory investment post-2030.

Network Implication 2: The electrification of heat will play an important role in Wales's heat transition, but other strategies should be explored to manage the impact of peak demand on the electricity distribution network.

Electricity networks are designed to meet peak demand, so reducing this can reduce the need for reinforcement requirements. Electrification of domestic heat and transport will be a major contributor to peak demand which will drive significant reinforcement, particularly in the distribution network. Whilst network operators should prepare for a substantial level of heat electrification, it is important to understand how other technologies and approaches can be

[107] RIIO-ED2 Final Determinations, Ofgem (2022) https://www.ofgem.gov.uk/publications/riio-ed2-final-determinations
[108] Long term development, National Grid (2023) https://www.nationalgrid.co.uk/our-network/long-term-development
[109]Long Term Development Statement, SP Energy Network (2022) https://www.spenergynetworks.co.uk/userfiles/file/SPM_Long_Term_Development_Statement_Nov_2022_Summary.pdf

leveraged to manage peak demand, and how a combination of these technologies may align within a local area. These options include behind-the-meter thermal storage, DSR, energy efficiency measures, behaviour changes, heat networks and the potential use of hybrid hydrogen boilers in some locations[110]. These are important options to minimise whole system costs by reducing peak demand, and the quantum of reinforcement required. DNOs should maximise the use of innovative approaches to minimise peak demand and accelerate their transition to a DSO, which will also help to optimise supply and demand at the distribution level.

Network Implication 3: Decarbonisation of industry in Wales needs coordinated planning and implementation support.

The decarbonisation choices made by large Welsh industrial demand assets will impact the Welsh energy network's transition. There is an opportunity for network companies, across vectors and transmission levels, to work with NZIW, other industry bodies, and Welsh Government to assess decarbonisation options of industry. Industrial clusters should coordinate more with networks and with Local Authorities when implementing LAEPs to make their roadmaps clear to other stakeholders.

Network Implication 4: Significant increases in renewable generation will require new electricity transmission network infrastructure.

A significant increase in renewable generation will be needed as Wales decarbonises. The analysis carried out in this project suggests that deployment of offshore wind is the lowest cost option for bulk power supply. However, if other renewable energy technologies such as onshore wind, solar PV and tidal were provided with additional support mechanisms such as improved CfD's or a more positive planning environment across all of GB, then their deployment in the future Welsh (and GB) energy system could increase.

Additional transmission network infrastructure would be needed to bring offshore electricity back onshore (or indeed to transmit electricity generated from increased deployment of onshore renewables such as onshore wind or solar) and detailed planning is underway[111]. This includes the North-South transmission link (see Recommendation 7 and section 11). To enable the high deployment of offshore wind needed, or other renewable generation capacity, the delivery of new transmission network infrastructure needs to be accelerated and this will require a regulatory framework which allows strategic and anticipatory investment. This is confirmed by NGESO's HND report[112].

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[110] Energy Security Bill factsheet: Enabling the Hydrogen Village trial, UK Government (2023) https://www.gov.uk/government/publications/energy-security-bill-factsheets/energy-security-bill-factsheet-enabling-the-hydrogen-village-trial

[111] Offshore Coordination Project - latest news and staying informed, NGESO (2023) https://www.nationalgrideso.com/future-energy/projects/offshore-coordination-project/latest-news

[112] The Pathway to 2030 Holistic Network Design, NGESO (2023) https://www.nationalgrideso.com/future-energy/pathway-2030-holistic-network-design#:~:text=The%20Pathway%20to%202030%20Holistic%20Network%20Design%20(HND)%20is%20a,it's%20needed%20across%20Great%20Britain

Network Implication 5: The continued and accelerated development of renewable energy across Wales will add to the challenges involved in ensuring stability in electricity distribution networks and balancing across the transmission network.

A large deployment of renewables, which create a supply with peaks and troughs, will increase the need to manage local operability challenges like voltage and fault level, as well as balancing across the whole electricity network. ESC's analysis using ESME suggests total renewable deployment (especially offshore wind in the Celtic Sea[113]) will continue to rise from 3GW in 2020 to 5.7GW and 6.6GW in 2030 and on to 16.1GW and 18.2GW by 2050, for Technology-Optimistic and Societally Optimistic respectively. Network operators will need to be able to plan for and access a range of market technologies including hydrogen-fired turbines, nuclear generation, DSR and batteries to meet these challenges, by procuring balancing services from storage and generation operators, as well as flexibility providers such as aggregators (see section 15).

Network Implication 6: The quantity, and production methods, of hydrogen could have a significant impact on electricity, natural gas and hydrogen networks in Wales.

There is uncertainty around the future scale of hydrogen production in Wales, as well as the technology that produces it. The analysis carried out in this project suggests that in one future scenario, deployment of large quantities of electrolysers between 2045 and 2050, largely to be exported to the rest of GB, could increase annual Welsh electricity demand by around 18TWh. This could have major implications for electricity network reinforcement, and the need for a hydrogen transmission network for export. However, the technological and business model deployed (e.g., hydrogen production coupled with offshore wind generation) will be a significant determinant of the type of network investment required. If blue hydrogen is produced in Wales, as it is in interim years in some scenarios, then this will create some demand for natural gas which will impact the need to retain parts of the natural gas network. Deployment of hydrogen to meet demand, largely for industry and shipping, is likely to be required in the medium- to longer-term, so network operators should understand the range of future quantities and production types of hydrogen, and adapt as the future of hydrogen becomes more certain. Network operators should also work with Welsh and UK Government to reduce future uncertainty around hydrogen.

Network Implication 7: Natural gas network operators should explore the need and value for a hydrogen transmission network in Wales.

Natural gas networks owners should continue to investigate the need for, design and feasibility of a hydrogen transmission network in Wales. As noted in Network Implication 6, uncertainty exists about hydrogen production methods and hydrogen's role within Wales and the rest of the UK's future energy system. However, this project has found it could start to be cost effective for the energy system for parts of industry and use in dispatchable power generation from the early to mid-2030's. Hydrogen production is possible from a variety of sources including electrolysers, natural gas with CCUS (blue hydrogen), nuclear heat and biomass. By 2050 the most cost-effective system is likely to include green hydrogen and some combination of the other sources. Detailed

[113] Although for this project ESC generally assumed offshore wind in the Celtic Sea connected to Wales, there may be additional capacity in the Celtic Sea connecting elsewhere, and capacity in the Irish Sea connecting to Wales. This is discussed further in section 10.2.1.

local analysis will be required to plan exact routes, but the need to transport hydrogen for these purposes away from potential production centres in North Wales (e.g., Deeside, Connah's Quay or Wylfa regions) and in South Wales at Pembroke, is likely.

Large scale hydrogen storage would be required to support hydrogen turbines in South Wales, which are expected to be needed to provide flexibility, system services and to meet peak domestic electrical heat demand. Whilst large scale hydrogen storage options in Wales should continue to be considered, it is likely that geological siting requirements will mean hydrogen storage in England will be required to support demand in Wales. This would require a hydrogen transmission network linking the potential storage facilities in England to the demand in Wales. However, if cost-effective large scale hydrogen storage options can be developed in Wales, then it may be economic for a transmission network to export hydrogen from Wales to England.

Network Implication 8: Demand Side Flexibility can reduce but not remove the impact of peak demands on electricity distribution networks.

DSR options, especially smart EV charging, and smart thermal storage enabled heating, can smooth electricity demand, helping to limit the impact of peak demands in Wales. This could reduce peak demand by 400MW, ~10% by 2050, based on the modelling carried out in this project (see section 11.2). This can impact how DNOs manage peak demands and so increased understanding of levels of smart charging and heating will be important. This should account for uncertainties such as the rollout of the required technologies, consumer engagement, development of suitable business models (e.g., aggregators) and the deployment of digital infrastructure needed to facilitate efficient DSR.

DNOs should harness demand side flexibility to aid in the efficient operation of the distribution networks as well as reducing the overall reinforcement needed, therefore reducing costs. However, rapid progress on developing DSOs and the associated markets and digital infrastructure required to access flexibility already in the energy system is fundamental to achieving this, so should be prioritised and accelerated. LEMs, which aim to establish a marketplace to coordinate energy use and demand within a local area, can be one way to promote the use of demand side options. DNOs/DSOs can then buy flexibility services which the LEM provides.

Network Implication 9: Energy system planning should be carried out on a whole system basis, aligning local, regional and national network activities. Designed and implemented correctly, the Regional System Planner (RSP) could play a crucial role in the medium-term, aligning local, regional and national network activities.

Network operators already engage substantially with Welsh Government. However, understanding the full implications of complex network activity for the Welsh energy system requires specialist knowledge. A whole system approach to effectively coordinate between Welsh Government aims, local plans and network investment plans would increase the likelihood of a cost efficient and optimised Welsh energy system compared to current institutional arrangements.

The precise role of the RSP is yet to be defined (and a separate function may be required in the near term – see Recommendation 12), however, if the RSP is able to effectively coordinate between Welsh Government aims, local plans and network investment plans, this could increase the likelihood of a cost efficient and optimised Welsh energy system compared to current institutional arrangements.

Network Implication 10: All energy networks should explore how whole system network planning can minimise transition costs.

This study highlighted the interactions between different energy vectors, for example the impact of other heat sources on electrical heat demand. It also highlights the need for coordination and engagement between a range of energy stakeholders including, Welsh Government, Local Authorities, network operators, industry and Welsh citizens. This demonstrates the need for whole system network planning, where all vectors and actors are considered when planning for energy network infrastructure, to minimise transition costs. Beyond this work, the Welsh Government's own Renewable Energy Deep Dive[114] and Ofgem's recent consultations[115] all reinforce the need for whole system planning. The challenge now is making this a reality. Welsh Government is uniquely positioned to support whole system network planning through their support of LAEPs across all Local Authorities in Wales. Network operators should engage with each other, Welsh Government and Local Authorities (on LAEPs and more broadly) and wider energy stakeholders to help ensure their network plans and investment process take a whole systems approach.

Network Implication 11: There is an important and increasing role for heat networks in a Net Zero Welsh energy system.

Heat networks can provide a meaningful contribution to total future heat demand in a cost-effective future Welsh energy system, particularly in urban areas with high population density, or areas near a large heat source (e.g. a cogeneration plant fuelled by nuclear power). Analysis from this project suggests heat network deployment could accelerate through the 2030s and provide around 15% (2TWh) of annual building heat demand in Wales by 2050. This could result in an increased number of heat network operators as well as an increased requirement for the skills required to install and operate them. Such networks are also subject to supply and demand variations due to differing demands across the year. As with the electricity system, a heat network solution must be able to accommodate extreme cold spells. The availability of local resource – for example, whether thermal plant or heat pump – will inform the nature of the heat network solution, with heat storage and backup ("peaking") boilers likely to be required.

[114] Renewable energy deep dive: recommendations, Welsh Government (2021) https://www.gov.wales/renewable-energy-deep-dive-recommendations
[115] Consultation: Future of local energy institutions and governance, Ofgem (2023) https://www.ofgem.gov.uk/publications/consultation-future-local-energy-institutions-and-governance ; Consultation on frameworks for future systems and network regulation: enabling an energy system for the future, Ofgem (2023) https://www.ofgem.gov.uk/publications/consultation-frameworks-future-systems-and-network-regulation-enabling-energy-system-future

PART C – APPENDICES

17. APPENDIX A

17.1. PROJECT APPROACH

ESME optimises the system for least cost, based on demand and technology assumptions, while ensuring targets are met. It does this for the whole UK system and allows the extraction of results from individual modelling regions, one of which is Wales. The modelling considers the complex interactions of power, gas, heat and transport, and the different ways in which energy might be supplied and used in the future. Assumptions used in the model include factors such as greenhouse gas (GHG) emissions targets, resource availability, and technology deployment rates and costs, as well as operational factors that ensure adequate system capacity and flexibility.

Figure 45 shows the high-level methodology followed in this work.

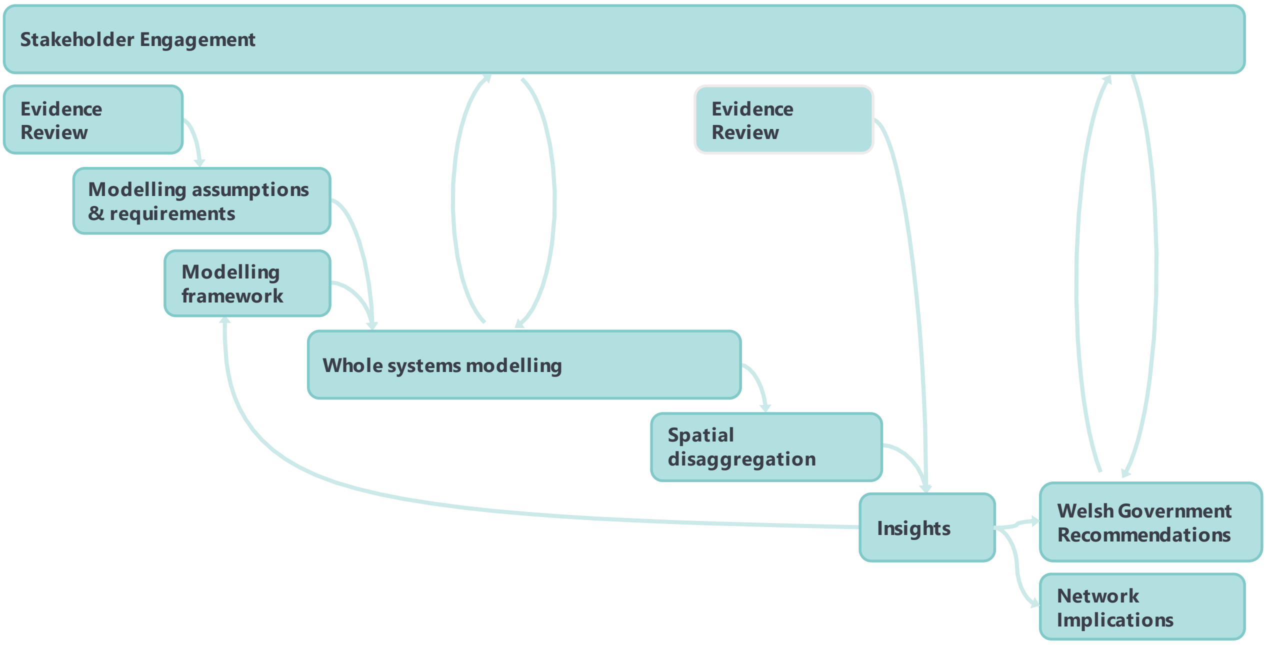

Figure 45: Process followed during FEW project

Key steps in the methodology:

- **Stakeholder Engagement:** Regular engagement with Welsh Government, Ofgem, the gas and electricity network companies operating in Wales, with occasional updates to a wider set of stakeholders. This engagement ensured a range of perspectives remained at the heart of the analysis and allowed outputs to be tested at key stages in the project.
- **Evidence review:** To ensure this work built upon the learnings of other studies, a robust evidence base was developed by reviewing network plans and existing literature, relevant either in geography, subject matter and/or approach. To complement this, relevant study authors and experts from Welsh Government, academia, and other informed organisations were consulted in semi-structured interviews.
- **Modelling assumptions and requirements:** Key modelling assumptions and requirements for this project were developed and tested with the network companies and Ofgem to ensure transparency. This was further informed by discussions with Welsh Government on energy system goals.
- **Modelling framework:** With support from stakeholders, ESC development of a set of scenarios and sensitivity scenarios.

- **Whole Systems Modelling:** Following agreement of energy system assumptions, whole system modelling of the scenarios was carried out using ESC's Energy System Modelling Environment (ESME) modelling tools.
- **Spatial disaggregation:** A second ESC tool, ESME Networks, was then used to provide additional insights by disaggregating the regional analysis of ESME into outputs at greater spatial granularity.
- **Insights:** Analysis of the possible Welsh energy system futures from the preceding research and modelling work resulted in a set of key insights.

The evidence generated through this research and analysis was used to deliver two primary outputs:

- **Welsh Government Recommendations:** Areas for Welsh Government focus and development in order to support the networks and the energy system in its transition to Net Zero.
- **Network Implications:** A set of considerations for network companies in the development of their detailed network planning.

18. APPENDIX B

18.1. EVIDENCE REVIEW AND STAKEHOLDER ENGAGEMENT

The future energy transition in Wales has been investigated by others in the past (See Appendix B). Reviewing the evidence from these studies provided an improved general understanding of the challenges and opportunities faced by the Welsh energy system, and provided some key insights that were reflected in the project.

The first part of the evidence gathering phase was a review of other energy system scenario work covering Wales. Throughout the project, as new literature was published, or was brought to the team's attention, additional reviews were carried out to ensure the work reflected ongoing learning in this area. An outline of the process and framework used is shown in Figure 4646.

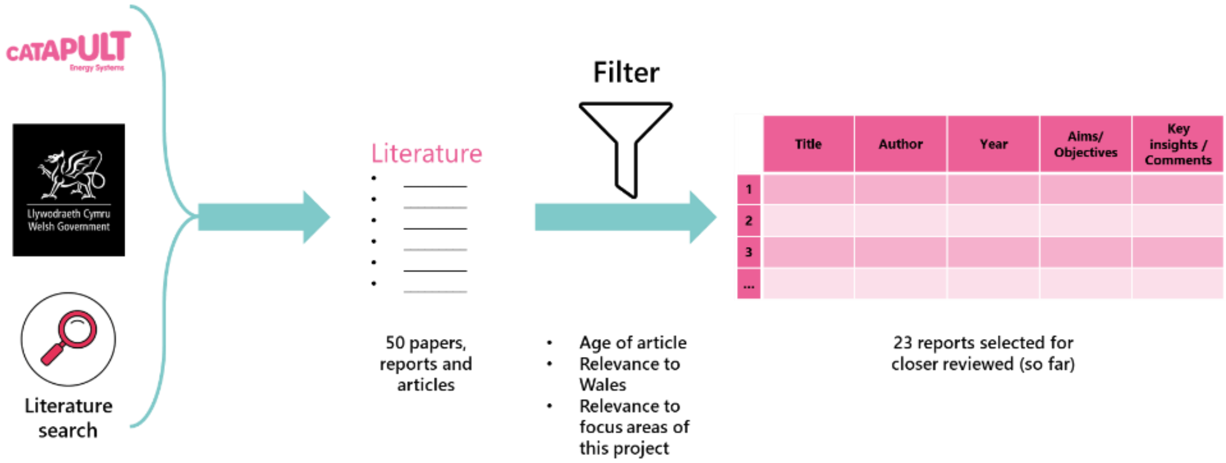

Figure 46: Literature review process and framework

A series of semi-structured interviews with experts from across the sector were carried out to build upon the insights gained from this initial literature review. A list of interviewees can be found in Appendix .

As well as this targeted approach, the project also involved an ongoing programme of stakeholder engagement to consult on emerging findings and gather further evidence. This was done with Welsh Government, energy network companies operating in Wales, and a group of wider stakeholders with interests in the Welsh energy system. The members of the latter two groups can be found in Appendix F. A total of 25 specific engagements and workshops were run during the project.

In all, seven main themes were identified during the evidence review, which are summarised in Table 3 and subsequently covered in further detail.

Theme	Summary
Targets and wider considerations	While emissions reduction targets may be seen as driving the energy system transition, wider technical, social, political and economic considerations are critical to its success.
Use of scenarios	Scenarios are successfully used to investigate areas of uncertainty. However, they should be clustered around a credible, realistic view of the future.
Representing people within the energy sector	People and the decisions they make are critical to the successful decarbonisation of Wales' energy system. Public sentiment and opinions are critical to the political acceptance of some of the steps needed in the transition.
Heat	The decarbonisation of domestic heating is one of the biggest challenges to be faced and there is huge uncertainty in the mix of solutions likely to be adopted. Non-technical and non-economic factors will play a significant part in any future pathway.
Industry	Much uncertainty remains in the direction of industrial decarbonisation. Coordination between businesses, network companies and government will be required to understand what viable pathways might look like, considering process, infrastructure and economic implications.
Transport	EV are the most likely route to decarbonise personal transport, with some mix of technologies used for HGVs.
Electricity	The electrification of heat and transport will lead to demand increases and will only lead to emissions reductions if electricity generation is decarbonised, through renewables and a mix of other solutions.

Table 3: Summary of findings from evidence review.

18.1.1. TARGETS AND WIDER CONSIDERATIONS

The statutory and aspirational targets announced by Welsh Government and others are ambitious, incorporating an emissions reduction trajectory to Net Zero in 2050, as well as targets around deployment of specific technologies. There are also several wider considerations that need to be addressed, adding to the challenge:

- Actions needed to achieve Net Zero are in the hands of everyone in Wales.
- Many of the paths forward are unclear, and there is considerable uncertainty when thinking about how technologies and demands might change over the next few decades.
- The decarbonisation of Wales and the wider UK are intrinsically linked. Many of the decisions affecting the transition in Wales rely on Westminster's approach.
    - It was stated during the interviews that two thirds of the required emissions reductions required in Wales are in areas where control is not devolved to Welsh Government.
- To ensure the decarbonisation of the energy system in Wales doesn't disproportionately impact any groups, it needs to be a just transition.
- Where at all possible, the opportunities presented by decarbonisation should be used to boost economic prosperity in Wales.

18.1.2. USE OF SCENARIOS

Previous work into Wales's energy system transition has used scenarios to explore the options available to Wales and their implications. Each takes a different approach; varying time horizons, sectors and energy vectors included, and geographical area. In general, two approaches to structuring the scenarios were seen:

- Narrative-based scenarios (input driven): A narrative is formed to explain how the future may unfold in terms of the inputs and assumption used.
- Outcome-based scenarios (output driven): Scenarios are defined in terms of selected key outputs of the modelling. The inputs are then varied to arrive at those scenario outcomes.

ESC[116], CCC[117], and NGESO[118] use a narrative-based approach. The scenarios are based on the variation of the level or speed of technological change, and the level of behavioural/societal change used in the assumptions. This is also adopted in much of the work of the DNOs and GDNs in their DFES. Figure 47Figure 47 shows NGESO framework.

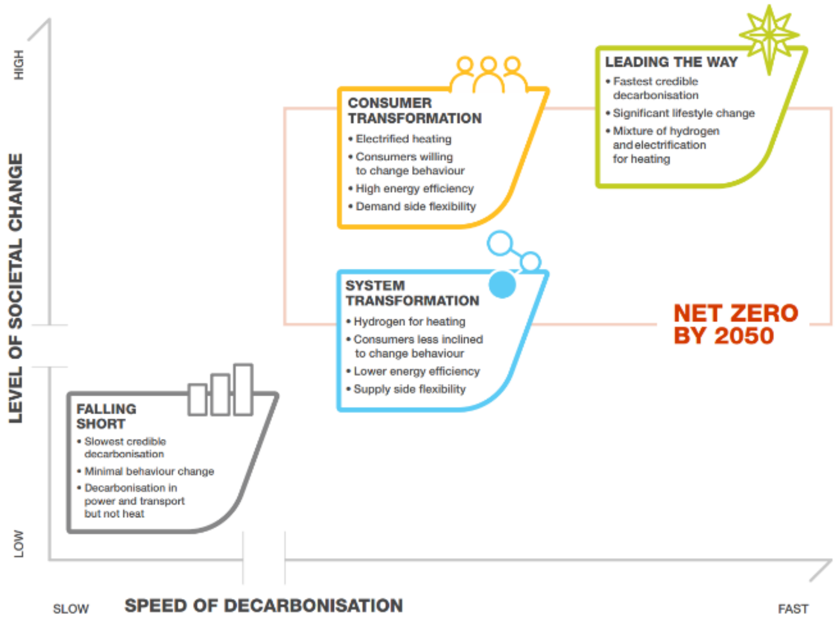

Figure 47: Scenario framework adopted in NGESO FES.

Work undertaken by ENA[119],Regen[120], and CR Plus[121] used outcome-based scenarios to look at the energy system transition. Figure 48Figure 48 shows an example of this approach, where different balances of hydrogen and electrification were investigated. These studies tended to look at the issues from an on-the-ground bottom-up viewpoint, whereas the more narrative based, input driven scenarios looked from top down, national strategy perspective. It was recognised in the literature that a combination of the two may deliver the most robust insights[122].

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[116] Innovating to Net Zero ESC (2020) https://es.catapult.org.uk/case-study/innovating-to-net-zero/
[117] 6th Carbon Budget Report CCC, 2020 https://www.theccc.org.uk/publication/sixth-carbon-budget/
[118] Future Energy Scenarios NG ESO, 2021 https://www.nationalgrideso.com/future-energy/future-energy-scenarios
[119] Gas Goes Green - Delivering the Pathway to Net Zero, ENA (2021) https://www.energynetworks.org/assets/images/ENA%20GGG%202021%20Programme.pdf
[120] A Combined Gas and Electricity DFES Assessment for South Wales, Regen (2020) https://www.regen.co.uk/wp-content/uploads/Net-Zero-South-Wales-Final.pdf
[121] CR Plus, 2020. *ZERO2050 South Wales*. https://zero2050.co.uk/media/1273/wst610_southwales2050_final.pdf
[122] CR Plus, 2020. *ZERO2050 South Wales*. https://zero2050.co.uk/media/1273/wst610_southwales2050_final.pdf

During the interviews with subject matter experts from across the sector, one point made was that there should be overlap between scenarios and they should be clustered around a credible, realistic view of the future. If this is done, it is possible to use them to find commonalities and therefore low regret actions.

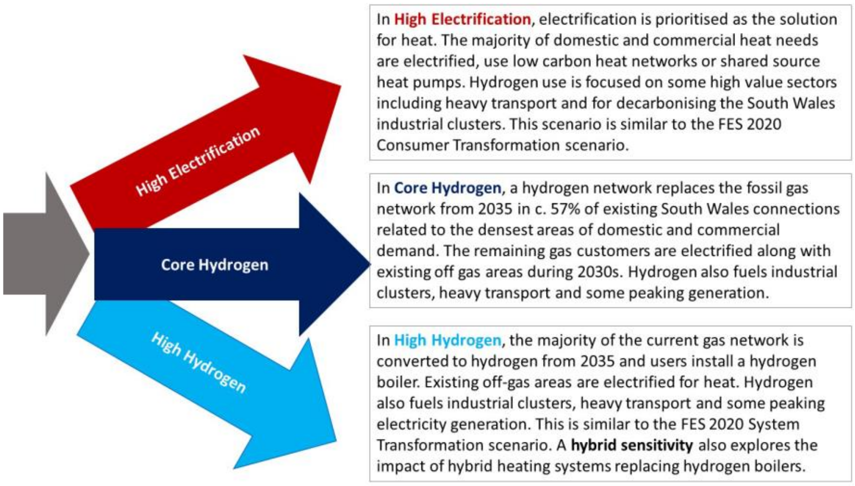

Figure 48: Outcome based scenario framework adopted in Regen's work.

18.1.3. REPRESENTING PEOPLE WITHIN THE ENERGY SYSTEM

An important insight from the interviews with sector experts was the reiteration of the importance of people in the transition of the Welsh energy system. It was reported that there was a growing appreciation by the citizens of Wales that sticking with the status quo is not possible. For example, they can't continue to use oil for heating in mid Wales, lifestyles will have to change, and infrastructure will have to be built if Wales' transition to Net Zero is to be achieved. This was followed up by a related point around the Welsh Government's perceived emphasis on behaviour change over technological solutions, and the recognition there are likely to be changes to all aspects of people's life.

The interesting interplay between technical, social, and political aspects was also highlighted. For example, public sentiment seems to have softened on large infrastructure, due to the climate emergency and the continued reliance on imported energy; a reflection that both sentiment and opinions are changing and that they are critical to the political acceptance of some of the steps needed in the transition.

Further important issues raised in this area focussed on the just transition and the importance of considering the impact of fuel poverty. Potential impacts could include:

- Home interventions may be too expensive for some and cause financial strain.
- Not carrying out the interventions may lead to higher energy bills than neighbouring properties who have carried them out.
- Some options may mean that, locally, energy may be more expensive/not available due to network decisions.

In each planning step in the transition, these are important factors to be fed into the decision making. They were also taken into account in the development of the insights from this study.

18.1.4. HEAT

The evidence review and stakeholder engagement identified that regionality is important to decarbonising heat in Wales, whilst the future of heat remains uncertain.

The continued combustion of natural gas in homes cannot continue if Wales is to meet its Net Zero target [123]. The alternatives are electrical systems (e.g., heat pumps, ERH), heat networks, the distribution of hydrogen to homes, or some hybrid of these.

Bio-methane may have a role in the transition in reducing the GHG intensity of natural gas (through blending)[124], and potentially for islanded networks[125]. However, from a whole system perspective, it is often found that the feedstock used to produce bio-methane would be better used elsewhere in the system[126] [127], particularly when the CO_2 can be captured to provide negative emissions.

The split of heating technologies is highly uncertain, with hydrogen seeing some of the widest variations in potential adoption in the literature. Different scenarios in the NGESO's FES work suggests the domestic hydrogen consumption could be anywhere between less than 5% to over half of today's domestic heat demand[128]. The literature consistently identified the short-term (5-10 years) applications for hydrogen are likely to be in industry (as discussed in section 6).

The interviews with sector experts confirmed this view of high uncertainty in approaches to meeting future heating needs. They also highlighted the non-technical and non-economic aspects that will play into the domestic heating pathway. A large part of the heating system decision is in the hands of policy makers and consumers but will also depend on the ability of supply chains and energy networks to scale up[129]. Without supportive policy signals and consumer propositions to drive adoption, any transition is going to be slow.

Another key point that emerged was the importance of looking at the challenges of decarbonisation of heat at different levels of granularity. Everywhere is different and there is a need for a mix of national, regional and local planning and activity [130]. This will better reflect the variations in local needs, such as variation in current heating provision (see Figure 49Figure 49), and of the variation in the energy efficiency of the housing stock.

There is general consensus that more should be done to accelerate demand reduction through energy efficiency.

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[123] Future Energy Scenarios NG ESO, 2021 https://www.nationalgrideso.com/future-energy/future-energy-scenarios
[124] Regional Growth Scenarios for Gas and Heat, Regen (2021) https://www.regen.co.uk/regional-future-energy-scenarios-for-heat-and-gas/
[125] Pathways to Net-Zero: Decarbonising the Gas Networks in Great Britain, ENA, (2019) https://www.energynetworks.org/industry-hub/resource-library/pathways-to-net-zero-decarbonising-the-gas-networks-in-great-britain.pdf
[126] Future Energy Scenarios NG ESO, 2021 https://www.nationalgrideso.com/future-energy/future-energy-scenarios
[127] 6th Carbon Budget Report, CCC (2020) https://www.theccc.org.uk/publication/sixth-carbon-budget/
[128] Future Energy Scenarios NG ESO, 2021 https://www.nationalgrideso.com/future-energy/future-energy-scenarios
[129] Growing the Supply Chain for a Net Zero Energy System, BEAMA (2022) https://www.beama.org.uk/resourceLibrary/growing-the-supply-chain.html
[130] Future Wales: the National Plan 2040 Welsh Government (2021) https://www.gov.wales/future-wales-national-plan-2040

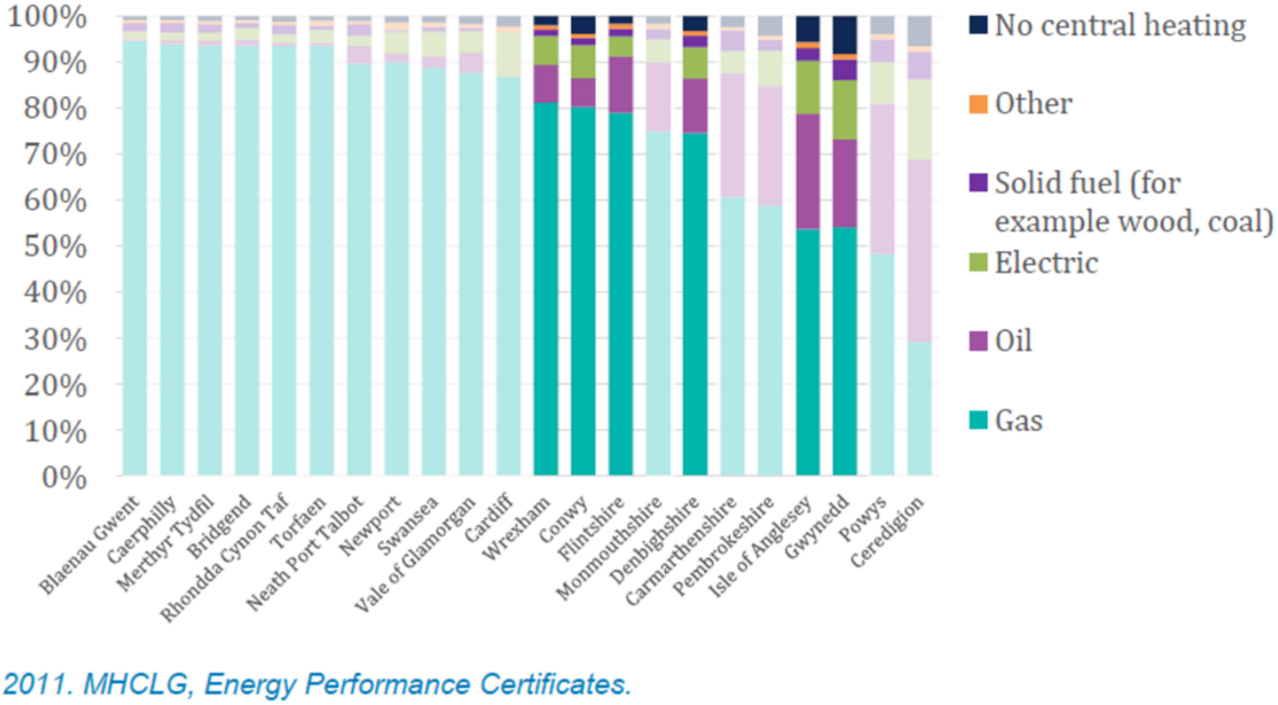

Figure 49: Proportion of homes heated by each heating fuel type in Wales, by local authority. Source: Regional Energy Strategy: North Wales, Ambition North Wales (2021).

18.1.5. INDUSTRY

Decarbonisation of Industry is something that appears to be accepted as a huge challenge. Wales has a few nuances that make it hard to tackle, as well as giving opportunities to move forward. For example, industrial activity is focussed in a small number of large sites, with three sites responsible for 91% of South Wales industrial emissions – a steelworks, a cement works and an oil refinery[131].

Industry faces a multi-faceted challenge of reducing energy demand, switching that energy demand away from GHG emitting sources, and addressing the issues around process emissions[132]. Although there are clear practical challenges, the first two of these – demand reduction and vector switching – can be achieved through continued process efficiency improvements and a move from fossil fuels to electricity or hydrogen for process heating[133]. Process fossil fuel use is likely to require significant process change and the development, and use of Carbon Capture and Storage (CCS)[134].

Much uncertainty remains in the direction of industrial decarbonisation. Some evidence suggested that H_2 is favoured as a replacement energy vector for natural gas, while some suggest electrification is a more sensible switch. Regardless, expectations varied on how the energy networks would adapt and transition to provide the necessary vectors. Coordination between businesses, network companies and government will be required to understand what viable industrial decarbonisation pathways might look like. Infrastructure and process change decisions

[131] CR Plus, 2020. ZERO2050 South Wales https://zero2050.co.uk/media/1273/wst610_southwales2050_final.pdf
[132] CR Plus, 2020. ZERO2050 South Wales https://zero2050.co.uk/media/1273/wst610_southwales2050_final.pdf
[133] Arup, 2021. Zero 2050 South Wales project: WP7 Integration and Optimisation https://zero2050.co.uk/work-packages/
[134] 6th Carbon Budget Report, CCC (2020) https://www.theccc.org.uk/publication/sixth-carbon-budget/

can then be made. There was also evidence of some industrial sites taking proactive steps by installing or contracting H_2 production on site.

The decisions made at each site have many considerations. One interviewee pointed out that the wide variety of industrial processes in need of a change will not have a one-size-fits-all solution. Each site will be making practical investment decisions alongside the need to decarbonise, and practicalities of supply chains and process experience will also come into consideration. It was also pointed out that sites will have multiple process lines which cannot feasibly be transitioned at one time and that it is unlikely to end with single vector feeding into all processes.

The final point was that many of the companies operating these sites are multi-nationals, so it is important that whatever steps are taken do not drive industry overseas and that Wales is continued to be seen as a good place to operate.

18.1.6. TRANSPORT

The evidence review and stakeholder engagement agreed that EVs are the most likely route to decarbonise personal transport [135] [136] [137] [138] with some mix of technologies used for HGVs, including H_2 [139]. It was raised, however, that wherever possible, modal shift to public transport should be encouraged as this reduces the overall demand.

18.1.7. ELECTRICITY

Electricity generation in Wales is expected to be 100% renewable by 2050, according to much of the literature reviewed [140]. However, some have highlighted the need for dispatchable generation to ensure supply can meet demand, with natural gas with CCS or H_2 playing their part in providing this.

Many interviewees highlighted the importance of electricity generation. The impact of electrification of transport and heat will lead to increased demand and only yield emissions savings if the electricity supply is decarbonised. It was reiterated that a mix of solutions will be needed.

The risk that an uncoordinated approach to new connections for renewable generation could deliver a very sub-optimal system was also highlighted, as was the need for a strategic solution rather than a reactive one. This will help with network planning but also in determining how much is reinforcement and how many new connections needed.

For offshore wind generation, the interviewees suggested that the opportunity is huge, but there are important constraints. For example, current network constraints and planning regimes will limit

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[135] Pathways to Net-Zero: Decarbonising the Gas Networks in Great Britain, ENA (2019) https://www.energynetworks.org/industry-hub/resource-library/pathways-to-net-zero-decarbonising-the-gas-networks-in-great-britain.pdf
[136] Future Energy Scenarios NG ESO, 2021 https://www.nationalgrideso.com/future-energy/future-energy-scenarios
[137] 6th Carbon Budget Report, CCC (2020) https://www.theccc.org.uk/publication/sixth-carbon-budget/
[138] Innovating to Net Zero, ESC (2020) https://es.catapult.org.uk/case-study/innovating-to-net-zero/
[139] Arup, 2021. Zero 2050 South Wales project: WP7 Integration and Optimisation https://zero2050.co.uk/work-packages/
[140] Advice Report: The path to a Net Zero Wales, CCC (2020) https://www.theccc.org.uk/wp-content/uploads/2020/12/Advice-Report-The-path-to-a-Net-Zero-Wales.pdf

the pace and scale of deployment, alongside competing marine interests (including environmental and shipping).

18.1.8. GENERAL

Alongside the themes described in the previous seven sections, the evidence review and stakeholder engagement identified broad agreement on the following points:

- Developments often come to light that override all projections – policy, technology or social change could come along and disrupt any pathway. For example:
  - The potential for tidal lagoons should not be ignored, there is huge technology and policy uncertainty there.
  - The drive for community ownership of distributed generation could sway the balance in the generation mix.
- There is a clear need for long-term planning that all actors can sign up to.
- Some level of central co-ordination and strategic planning is needed so that the challenges can be approached from holistic viewpoint.

19. APPENDIX C

19.1. MODELLING APPROACH

The initial review and stakeholder engagement activities highlighted a great deal of complexity and richness within the multiple needs of the Welsh energy system for the modelling to assess. In response, an extensive and structured programme of activity was developed to provide insights to Welsh Government and the networks operating in Wales to support future planning activity.

The approach broke down the complexity into a smaller set of questions which were developed through a series of stakeholder workshops. Figure 50 shows a high-level representation of the steps taken, which are detailed in the following sections.

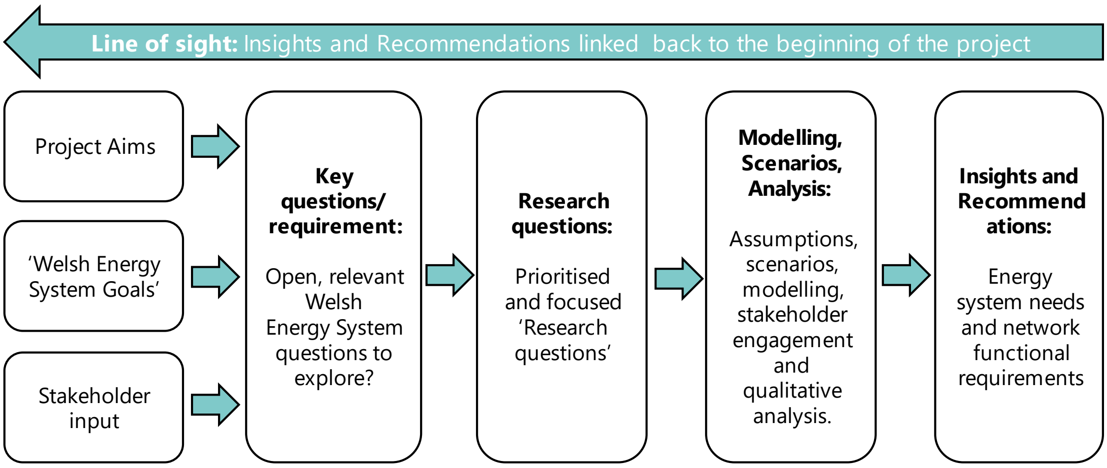

Figure 50: Modelling Approach

19.1.1. WELSH ENERGY SYSTEM GOALS

A set of Welsh Energy System Goals are listed in Table 4 and Table 5 that were developed in collaboration with Welsh Government with the aim to capture the goals of a broad range of stakeholders involved in the system, from national bodies to individual citizens of Wales. This list is split into two, the first being goals that are specific to the Welsh energy system and the second being goals that reflect the operational interaction with the wider GB energy system but are still important and relevant to the Welsh energy system.

Goal title	Description
The Welsh Energy System Shall…	
…generate enough energy to meet Welsh needs	*Welsh production shall fully meet energy needs across all vectors. Requires balance of green generation technologies to ensure energy security. Will not necessarily meet demand minute by minute but generally on an annual basis.*
…generate surplus energy to tackle nature and climate emergencies	*Protecting land use and the environment for nature and supporting the rest of the UK or global energy system with green energy generation if available. A surplus should generate benefit and value to Wales.*
…reduce energy demand	*Accelerate actions to reduce energy demand while continuing to deliver the energy service needs of Welsh citizens.*
…maximise economic and social benefits in Wales	*Maximise local ownership of energy assets and leverage the value chains for the energy transition to retain the economic and social benefits in Wales.*
…be flexible and smart – maximise the ability to match local energy generation with demand	*A smart energy system using data, information and technology that enables flexibility and optimal use of local generation resources.*
…contribute to Wales being a globally responsible citizen in terms of energy.	*Wales should not be relying on others for their energy if they are capable of generating it themselves. Ensure that Wales does not import energy from carbon emitting sources if more green sources of energy are available either in or outside of Wales*
…consider optimal use of land and marine resource	*Ensure a balance between, agriculture, nature and energy generation in different regions.*
…be part of the wider GB energy system	*Greater diversity of supply and demand to ensure greater security of supply while being a globally responsible citizen*
…Meets Net Zero by 2050 and interim carbon budgets	*Ensure the system meets the Welsh legal targets and contributes to the UK targets*

Table 4: Welsh Energy System Goals and brief descriptions

Goal title	Description
The GB Energy System Shall…	
…be stable and have security of supply	*An energy system that is available when needed and reliable when used and has stability of price. Redundant and back up energy options available.*
…be safe and secure	*A safe energy system to society, public and employees of asset owners. An energy system protected from physical and cyber threats.*
…be an affordable system	*The energy system will be efficient and affordable for consumers "A just transition" and stakeholders "optimal cost of infrastructure investment".*

Table 5: GB Energy System Goals and brief descriptions

19.1.2. RESEARCH QUESTIONS

Through a process of iterative refinement, the Welsh energy system goals, combined with the learnings from the preparatory evidence gathering led to a set of focussed research questions being developed. These allowed targeted analysis with the ESME modelling tools. The research questions, once developed, ensured the project had a framework on which to work. The research questions formed a hierarchy with three primary questions at the top, as detailed in Figure 51Figure 51. The insights were developed to respond to these three questions, as well as highlighting other insights identified through the process.

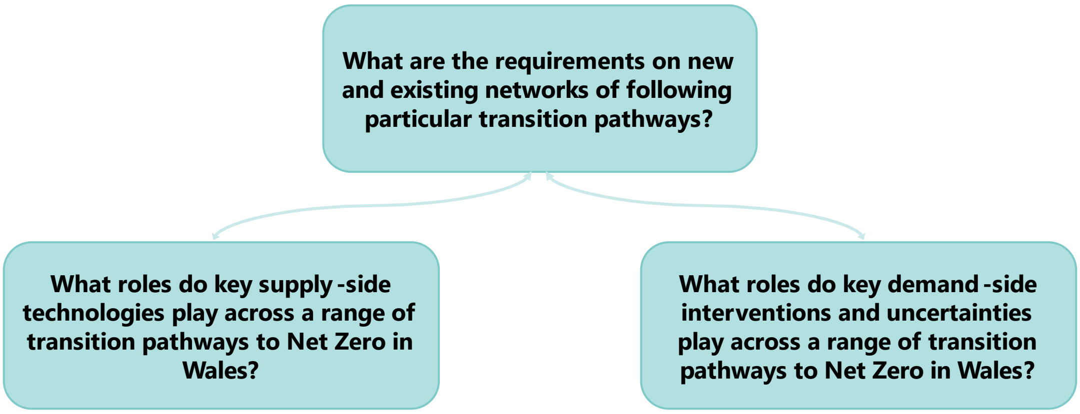

Figure 51: Research Questions to be addressed by the modelling

Additional research questions were developed and sit in the hierarchy under the three primary questions. These are more specific to focus on what can be modelled or addressed via other means (such as literature review). ESC aimed to provide insights to all research questions with the answers combined to address the primary questions. The additional research questions are listed as follows:

- What are the consequences of pursuing a Welsh energy system including high volumes of renewables?
- What are the consequences of varying balance between offshore and onshore wind?
- What are the impacts on the Welsh energy system of Welsh Government actively supporting interventions they have influence over?
- How do different Welsh Government levels of ambition and targets influence the timing and extent of any intervention in the energy system
- What impact can behaviour change have on the energy system and can it be relied on at peak times?
- What impact does the cost of building retrofit have on uptake and the balance between supply side and demand side interventions?
- How does the adoption of hydrogen as a central energy carrier influence Wales's transition to Net Zero?
- What is the system impact of progressing specific major asset developments (e.g. Wylfa)?
- How do the Wales and GB energy systems interact within putative transitions to Net Zero?*

*Questions were not possible to model so were explored via literature review.

With these questions developed the modelling activities could commence.

19.1.3. ASSUMPTIONS AND RESEARCH QUESTIONS

The future energy system is uncertain and will be impacted by different uncertainties such as technology costs, efficiencies, demands, policy, consumer preferences and more. Such uncertainties can be projected but are not known absolutely. This is why appropriate research, supported by energy systems modelling, can help improve understanding of the potential future needs and evolution of the energy system whilst taking such uncertainties into consideration. Within this project the ESME model has been used. This is an industry leading Whole Energy System Optimisation Model (WESOM), developed over fourteen years and trusted by organisations across the energy sector. The aim of ESME is to take any given set of assumptions (such as GHG emissions targets, projected energy service demands, technology cost/performance/availability, etc) and determine the lowest-cost energy system. This is illustrated in Figure 52.

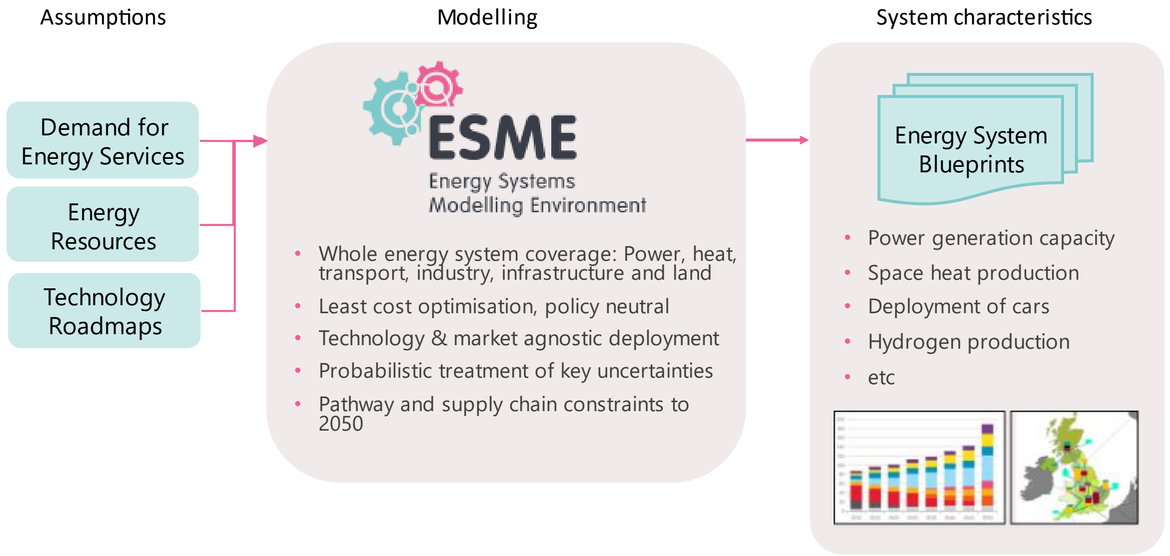

Figure 52: ESME, (Note graph and map are for example purposes only)

In this project, this approach has been further supported by ESC's ESME Networks model, which takes the ESME output from Wales as a national view and disaggregates into a regional view. The results of the ESME and ESME Networks modelling can be seen from Section 3 onwards.

19.1.4. MODELLING ASSUMPTIONS

The range of assumptions noted above can be taken from a variety of sources and require the stakeholders involved with the project to assess and agree on the detail within them to inform the modelling. This ensures that stakeholders have a common understanding of the baseline assumptions before the modelling activity commences.

ESME has been used extensively and has an established set of assumptions that have been tested and updated on various occasions. It is important for key project stakeholders to agree on their details. However, the list of assumptions is large with over 300 technologies and over 50 end-use product demands which made it impractical to present them all. To support this, ESC refined the assumptions down to a key set according to importance, relevance, and impact. Additionally, it was relevant for ESC to internally evaluate the 'robustness' of all the assumptions as this may affect the way in which these assumptions were presented to stakeholders.

Table 6describes updates to assumptions used within the ESME model implemented within this project. Historic assumptions are available in the public domain, e.g. via:

https://ukerc.rl.ac.uk/ETI/PUBLICATIONS/ESME-v4.3-Dataset.pdf

Category	Technology / resource	Characteristic	Units	Assumption (1)	Assumption (2)	Source / comments
Energy conversion	**H2 Plant (Electrolysis)**	Efficiency	kWh.e / kWh.H2	(2020) 1.4	(2050) 1.2	BEIS H2 Supply Chain Evidence Base (https://www.gov.uk/government/publications/hydrogen-supply-chain-evidence-base)
	H2 Plant (Biomass Gasification with CCS)	Capital cost	£/kW.H2	(2020) 2280	(2050) 1160	Own analysis
	H2 Plant (Biomass Gasification with CCS)	Maximum deployment rate	GW / year	(2030) 0.2	(2050) 2	Own analysis
	Solar PV	Existing / in-flight capacity	MW	(Domestic rooftop) 240	(Utility-scale) 770	Government statistics (e.g. Energy Generation in Wales 2020, https://www.gov.wales/sites/default/files/publications/2022-06/energy-generation-in-wales-2020.pdf)
	Onshore Wind	Minimum deployment quantities	GW	(2030-2050) 3		Reflecting repowering / life-extension of existing / in-flight capacity
	CCGT / CCS / H2 Turbine	Availability	Various			Aligning to policy wherein minimal unabated fossil plant is permitted to operate from the 2030s
	Nuclear (Gen III)	Minimum deployment quantities	GW	(2030) 3.2	(2035) 6.4	Reflecting expected first generation from Hinkley Point C and Sizewell C
	Nuclear (SMR)	First availability	Year	2035		Includes 5 year slowing of first availability versus ESME v5.0
	Nuclear (Gen IV)	First availability	Year	2040		Includes 5 year slowing of first availability versus ESME v5.0
Heat	**ERH**	Efficiency	kWh.e / kWh.heat	(2020) 1	(2050) 1	Own analysis
Infrastructure	**Hydrogen transmission infrastructure**	TX pipeline length				Own analysis of pipeline lengths based on Project Union / existing natural gas infrastructure
Energy Resource	**Offshore wind resource in Wales**	Maximum resource accessible	TWh / year	Shallow water resource: 67	Deep water resource: 21	Private issue of data from NGESO for use in this project only
Non-energy	**Non-energy-related GHG emissions projections**	Emissions	tCO2e / year	Projections between 10 MtCO2e and 31 MtCO2e		Climate Change Committee, Sixth Carbon Budget (https://www.theccc.org.uk/publication/sixth-carbon-budget/)
	Energy-related CO2 emissions targets	Emissions target	tCO2 / year	(2050) -35 MtCO2		Derived from non-energy-related GHG emissions projections

Table 6: List of updated assumptions used within the project

19.1.5. MODELLING

In most modelling applications, scenarios are developed "… to help decision makers develop their own feel for the nature of the system, the forces at work within it, the uncertainties that underlie the alternative scenarios, and the concepts useful for interpreting key data…"[141]

In this project, the approach adopted was scenario analysis with "sensitivity scenarios" to explore wide range of multiple possible future pathways to a Net Zero Welsh energy system by 2050.

The baseline scenarios used as reference points for analysis are Technology-Optimistic and Societally Optimistic which provide two possible future worlds of relevance for Wales. These two possible future worlds and their characteristics are described in Figure 53. Figure 54 and Figure 55 further summarise this process of using sensitivity scenarios.

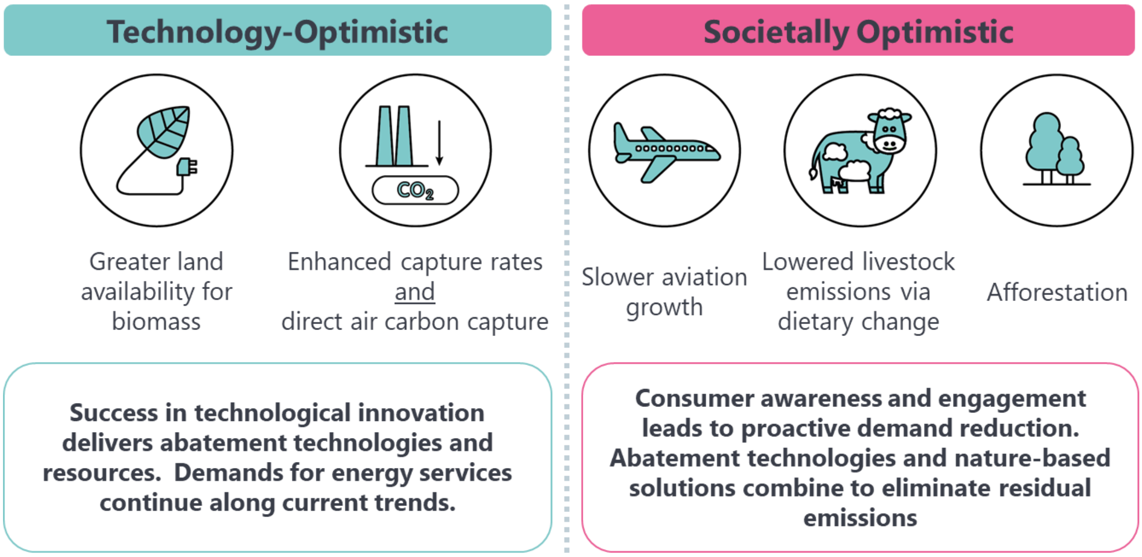

Figure 53: Summary of the Technology-Optimistic and Societally Optimistic reference scenarios

[141] Quote on scenario modelling referenced from Shell

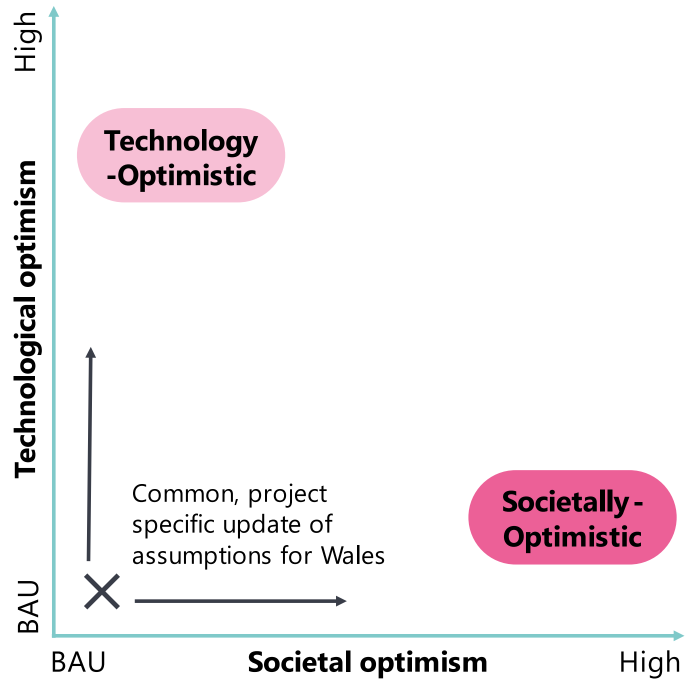

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Figure 54: Scenarios framework and the position of the Technology-Optimistic and Societally Optimistic scenarios in it.

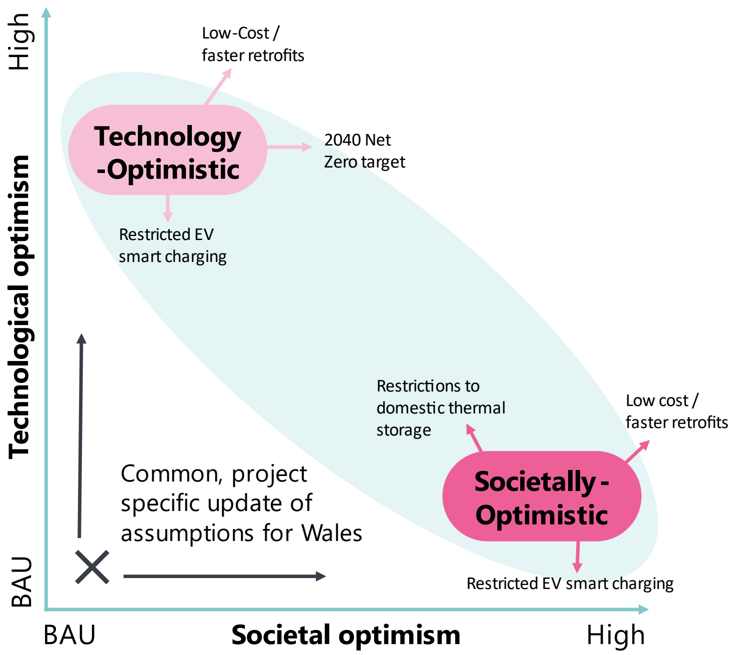

Figure 55: Example of how the use of sensitivity scenarios expand the range of future energy systems considered

Figure 54 and Figure 55 shows how sensitivity scenarios can be used to expand the range of future energy systems considered. Each sensitivity scenario changes one variable in either the Technology-Optimistic or the Societally Optimistic scenario which moves the scenario up/down or left/right along the scenario framework, thus expanding the envelope of future systems which are considered (the blue area in Figure 55). Figure 54 shows example variables which were changed to create some of the sensitivity scenarios. For example, a sensitivity scenario which restricts electric vehicle smart charging compared to either Technology-Optimistic or Societally Optimistic, shows a reduction in both technology innovation and societal change and so moves these scenarios to the left and down the framework.

The sensitivity scenarios used, and the variable each one changes, were generated by assessing the assumptions that would allow ESME to address the research questions. In some cases these warrant testing against multiple scenarios (e.g. if there was a possible expectation of different outcomes for different future worlds). Although some of these cases are already apparent, it was expected that this would become visible after initial modelling runs. The research questions and specific sensitivity scenarios proposed are described in Table 7.

Scenario Name	Description	Research Question (see section 19.1.2)
Technology-Optimistic	A scenario which reaches Net Zero by 2050 with a focus on technical optimism	Used as reference cases for all research questions
Societally Optimistic	A scenario which reaches Net Zero by 2050 with a focus on societal optimism	
100% OPTIMAL	A scenario where renewable energy originating in Wales is equal to energy consumed in Wales	What are the consequences of pursuing a Welsh energy system including high volumes of renewables?
100% SOLAR	As 100% OPTIMAL but with an increased proportion of renewable energy being provided by solar	
100% WIND	As 100% OPTIMAL but with an increased proportion of renewable energy being provided by wind	
125% OPTIMAL	A scenario where renewable energy originating in Wales is 1.25 x energy consumed in Wales	
150% OPTIMAL	A scenario where renewable energy originating in Wales is 1.5 x energy consumed in Wales	
LOW COST SOLAR	A scenario with a sustained low hurdle rate for solar PV in just Wales	
LOW COST SOLAR (UK)	A scenario with a sustained low hurdle rate for solar PV in all of the UK	
HIGH ONSHORE WIND	A scenario with an increased proportion of electricity generation from onshore wind	What are the consequences of varying balance between off-shore and on-shore wind
HIGH OFFSHORE WIND	A scenario with an increased proportion of electricity generation from offshore wind	
LOW ONSHORE	A scenario with no repowering of onshore wind	
LOW COST ONSHORE	A scenario which assumes additional policy support and public acceptance of onshore wind	
TOC Net Zero WALES 2045	The Technology-Optimistic scenario with a 2045 Net Zero target for Wales	How do different Welsh Government levels of ambition and targets influence the timing and extent of any intervention in the energy system?
SOC Net Zero WALES 2045	The Societally Optimistic scenario with a 2045 Net Zero target for Wales	
TOC Net Zero WALES 2040	The Technology-Optimistic scenario with a 2040 Net Zero target for Wales	
SOC Net Zero WALES 2040	The Societally Optimistic scenario with a 2040 Net Zero target for Wales	
TOC LOW HEAT STORAGE	Restrictions to rollout of behind-the-meter heat storage	What impact can behaviour change have on the energy system and can it be relied on at peak times?
SOC LOW HEAT STORAGE	Restrictions to rollout of behind-the-meter heat storage	
TOC LOW EV SMART CHARGING	Restrictions to EV smart charging	
SOC LOW EV SMART CHARGING	Restrictions to EV smart charging	
TOC RETRO LOW	A Technology-Optimistic scenario with low cost insulation retrofits	What impact does the cost of building retrofit have on

TOC RETRO ULTRA LOW	A Technology-Optimistic scenario with ultra low cost insulation retrofits	uptake and the balance between supply side and demand side interventions?
TOC RETRO HIGH	A Technology-Optimistic scenario with high cost insulation retrofits	
SOC RETRO LOW	A Societally Optimistic scenario with low cost insulation retrofits	
SOC RETRO ULTRA LOW	A Societally Optimistic scenario with ultra low cost insulation retrofits	
SOC RETRO HIGH	A Societally Optimistic scenario with high cost insulation retrofits	
TOC EARLY RETRO	A scenario like TOC.RETRO ULTRA LOW but with insulation retrofits brought forward by a decade	
TOC ADJUSTED ELECTRIFICATION	The Technology-Optimistic scenario but with barriers lifted to allow deployment of ASHPs into the entire domestic / non-domestic building stock, not just those houses with minimum levels of insulation,	
NO H2	A scenario with no hydrogen available	How does the adoption of hydrogen as a central energy carrier influence Wales's transition to Net Zero?
NO H2 REPURPOSE	A scenario with no hydrogen repurposing (i.e. no hydrogen in local distribution networks)	
BLUE CAPTURE	A scenario with blue hydrogen available but lifecycle capture rate (including upstream) lower	
BLUE COST	A scenario with blue hydrogen present but at a higher lifecycle cost	
GREEN COST	A scenario with green hydrogen present but at variable cost points	
NO H2 BECCS	A scenario with failed innovation to produce hydrogen from biomass at scale	
H2 COMBI BOILERS	A scenario with hydrogen use in buildings limited to combination boiler replacements (no hybrids)	
INCREASED ELECTRIFICATION	A scenario where a full electrification switch is implemented at a large industrial demand site in Wales	
INCREASED H2 AVAILABILITY	A scenario where a full hydrogen switch is implemented at a large industrial demand site in Wales	
TOC ADJUSTED ELECTRIFICATION NO H2	A scenario the same as TOC ADJUSTED ELECTRIFICATION but no availability of hydrogen boilers	
WYLFA GEN III	A scenario including a 2 unit nuclear Gen III+ plant at Wylfa	What is the system impact of progressing specific major asset developments?
WYLFA light water SMR	A scenario including a multiple unit light-water SMR unit at Wylfa	
H2 CLUSTERS	A scenario with hydrogen as the adopted industrial solution in North and South Wales	
TIDAL BARRAGE	A scenario including a single tidal barrage / lagoon system	
NO PIPE CCS	A scenario with delayed CCS availability due to absence of infrastructure	

Table 7: Research Questions and Sensitivity Scenarios

20. APPENDIX D

20.1. LITERATURE REVIEW LIST

	Title	Author	Year
1	Advice Report: The Path to Net Zero for Wales	CCC	Dec-20
2	Conwy Local Area Energy Plan (p48)	Conwy Council/Arup	Feb-22
3	DFES - South Wales licence area - Results and Assumptions Report	Western Power Distribution (WPD)	2021
4	Electricity Ten Year Statement	NGESO	2021
5	EV Charging Strategy	Welsh Government	Mar-21
6	FES	NGESO	Jul-21
7	Future Potential For Offshore Wind	Carbon Trust for Welsh Gov	Dec-18
8	Future Wales: the National Plan 2040 - includes PAAs for renewables	Welsh Government	Mar-21
9	Long Term Development Statement 2021	Wales and West Utilities	2021
10	National Population Projections	ONS	Jan-22
11	Net Zero South Wales 2050 - A combined gas and electricity DFES assessment for South Wales to 2050 - Learning Report	Regen for Wales & West Utilities (WWU) and (WPD)	Jun-20
12	Net Zero Wales Low Carbon delivery plan for the second carbon budget	Welsh Government	Oct-21
13	Network Options Assessment	NGESO	Jan-22
14	Offshore wind and grid in Wales (technical report available by request)	Welsh Government	2021
15	Regional Energy Strategy: Cardiff Capital Region	CCR	Dec-20
16	Regional Energy Strategy: Mid Wales	Welsh Government/WGES/Powys/Ceredigion	2021
17	Regional Energy Strategy: North Wales	Ambition North Wales	2021
18	Regional Growth Scenarios for Gas and Heat - Phase 3: Wales regional assessment - Technical report and summary results	Wales and West Utilities	Sep-19
19	Report on the Climate Change (Wales) Regulations 2021	Welsh Parliament	Mar-21
20	SP Manweb FES	SPEN	Nov-21
21	Strategic Wider Works	OFGEM	Mar-19
22	Zero 2050 South Wales project: WP 5 Industry	CR Plus	Jun-20
23	Zero 2050 South Wales project: WP7 Integration and Optimisation	Arup	Jul-21

Table 8: Literature Review List

21. APPENDIX E

21.1. EXPERT ENGAGEMENT INTERVIEWEES

Interviews conducted with:

- John Howells – Director of Energy, Climate Change and Planning, Welsh Government
- Rhys Jones – Director RenewableUK Cymru
- Chris Williams – Head of Industrial Decarbonisation, Industry Wales (Seconded from Tata Steel)
- Jon Maddy – Director, Hydrogen Research Centre, University of South Wales
- Professor Jianzhong Wu – Head of School, Engineering, Cardiff University, Co-Director of UK Energy Research Centre (UKERC), Associate-Director of EPSRC Supergen Energy Networks Hub

22. APPENDIX F

22.1. STAKEHOLDER GROUPS

Energy Network Companies:

- Office of Gas and Markets (Ofgem)
- National Grid Electricity System Operator (NGESO)
- National Grid Electricity Transmission (NGET)
- National Grid Gas Transmission (NG GT) – (National Gas Transmission (NGT) in latter stages of project)
- Wales & West Utilities (WWU)
- SP Energy Networks (SPEN)
- Western Power Distribution (WPD) – (National Grid Electricity Distribution (NGED) in latter stages of project)

Wider attendees at public webinars:

- ADE
- Ambition North Wales
- British Hydropower Association
- Campaign for National Parks
- Campaign for the Protection of Rural Wales
- Cardiff Capital Region
- Citizens Advice
- Community Energy Wales
- Confederation of British Industry (CBI)
- Country Landowners Association
- Energy Networks Association
- EnergyUK
- Farmers Union of Wales
- Federation of Small Businesses (FSB)
- Friends of the Earth Cymru
- Future Generation Commissioners Office
- Groundwork Wales
- Growing Mid Wales
- Innovate UK
- Institute of Welsh Affairs
- LG Decarbonisation Sector Panel
- Local Authorities Planning Officers
- Media and External Relations Manager, Cardiff; and Director of Analysis
- National Infrastructure Commission for Wales
- National Parks Organisation - Brecon Beacons
- National Parks Organisation - Pembrokeshire Coast
- National Parks Organisation - Snowdonia
- Natural Resources Wales - Commercial delivery
- Natural Resources Wales - Commercial Director
- Natural Resources Wales Policy Lead
- NFU Cymru
- Nuclear Industry Association
- One Voice Wales
- Ramblers Cymru
- RSPB Wales

- Solar Energy UK
- Swansea Bay City Region
- WCVA
- Welsh Government Energy Service
- Welsh Government Energy Service (Cardiff City Region)
- Welsh Government Energy Service (North/Mid Wales)
- Welsh Government Energy Service (South West Wales)
- WLGA (Welsh Local Government Association)
- WWF

23. APPENDIX G

23.1. GLOSSARY

Acronym	Meaning
ASHP	Air Source Heat Pumps
ASTI	Accelerated Strategic Transmission Investments
BECCS	Bioenergy with Carbon Capture and Storage
BEIS	Business, Energy & Industrial Strategy
CCC	Climate Change Committee
CCGT	Combined Cycle Gas Turbine
CCUS	Carbon Capture Utilisation and Storage
CfD	Contracts for Difference
CSNP	Centralised Strategic Network Plan
DESNZ	Department of Energy Security and Net Zero
DFES	Distribution Future Energy Scenarios
DNO	Distribution Network Operators
DSO	Distribution System Operators
DSR	Demand Side Response
ENC	Electricity Networks Commissioner
ERH	Electric Resistive Heating
ESC	Energy Systems Catapult
ESME	Energy System Modelling Environment
ETI	Energy Technologies Institute
EV	Electric Vehicles
FES	Future Energy Scenarios
FEW	Future Energy Grids for Wales
FSNR	Future System Network Regulation
FSO	Future System Operator
GB	Great Britain
GDN	Gas Distribution Network
GHG	Greenhouse Gas
HND	Holistic Network Design
HVAC	Heating, Ventilation & Air Conditioning
ICE	Internal Combustion Engine
LAEP	Local Area Energy Plan
LEM	Local Energy Market
LEO	Local Energy Oxfordshire
LNG	Liquefied Natural Gas
LMP	Locational Margin Pricing
LTDS	Long-Term Development Statement
NGED	National Grid Electricity Distribution
NGESO	National Grid Electricity System Operator
NGET	National Grid Electricity Transmission
NGT	National Gas Transmission
NPR	Network Planning Review
NTS	National Transmission System
NZIW	Net Zero Industry Wales

OFGEM	Office of Gas and Electricity Markets
PV	Photovoltaic
REMA	Review of Electricity Market Arrangements
RSP	Regional System Planner
SMRs	Small Modular Reactors
SPEN	SP Energy Networks
SOC	Societally Optimistic
SWIC	South Wales Industrial Cluster
TOC	Technology-Optimistic
UK	United Kingdom
UKERC	UK Energy Research Centre
WESOM	Whole Energy System Optimisation
WLGA	Welsh Local Government Association
WPD	Western Power Distribution
WWU	Wales & West Utilities

LICENCE/DISCLAIMER

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