Scottish whole energy system scenarios

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Executive Summary

In 2019, Scotland set a target to achieve net zero emissions by 2045, one of the most ambitious national targets in support of climate change mitigation. This includes an interim target to reduce Scotland's 2030 emissions by 75% compared to 1990 and annual targets for all other years from now to net-zero. To deliver on these targets, Scottish Government has set out a series of sector specific policies and measures, collated and summarised in the 2020 Update to the Climate Change Plan (CCPu).

In this project, Scottish Government and the ClimateXChange commissioned Energy Systems Catapult (ESC) to develop a set of Scotland-specific whole energy system scenarios, nested in and consistent with the wider UK transition. These scenarios demonstrate three qualitatively different routes for Scotland to meet its greenhouse gas (GHG) targets, allowing different choices and potential implications to be explored.

The scenarios were commissioned to inform thinking, encourage debate, and evaluate options. They are not fixed pathways, mutually exclusive or an exhaustive list of options Scotland could follow to meet GHG targets. Nor do they provide specific solutions to the net zero transition. They were also not designed to meet the full range of Scotland's wider statutory obligations, for example in relation to fuel poverty.

It should be noted that this modelling was undertaken prior to the recent geopolitical events in Ukraine and changes in natural gas market prices. Sustained increases in natural gas price are likely to have a noticeable effect on the modelling especially on the economics of hydrogen and the balance between blue and green hydrogen production. Further sensitivity analysis will be required to understand the full impact of a sustained rise in natural gas price on Scotland's transition to Net Zero.

Scenarios

Three scenarios met Scotland's annual, interim (2030) and net zero (2045) GHG targets over the modelled period 2020-2050, through different combinations of technology innovation and societal change.

1. The **Technology (TEC) scenario** is able to remove significant amounts of CO_2 by direct air carbon capture and storage (DACCS) and bioenergy with carbon capture and storage (BECCS) used to produce hydrogen and electricity. This reduced the level of societal change necessary to meet targets thus minimising the impact on people's lifestyles.
2. The lower energy demands assumed in the **Societal Change (SOC)** scenario meant targets were achievable with far lower amounts of biomass and engineered removals of CO_2. In addition, shifts in diet from red meat and dairy, combined with ambitious

programmes of peatland restoration and afforestation, meant land use became a net GHG sink.

3. **Balanced Options (BOP)** combined some technology innovation with some degree of societal change to meet GHG targets in a more balanced way than TEC or SOC.

The scenarios demonstrate the potential and indeed need for innovation in both technology and behaviour. Technology innovation can help mitigate the risk that people are unable or unwilling to modify their current habits and lifestyles. Conversely, if society does adopt new, lower carbon ways of living, then Scottish (and UK) GHG targets may be less reliant on successful technology innovation. This is especially important when considering emerging technologies such as DACCS and BECCS.

Insights

- Rapid decarbonisation of the energy system is needed in all modelled scenarios to meet Scotland's 2030 GHG target. Renewable generation is likely to become the workhorse of any Scottish power sector.
- There will be a strong role for on and offshore wind in Scotland. Scotland is likely to both meet domestic needs and be a significant net exporter of electricity to the rest of UK (ROUK) – for example, in the TEC scenario two thirds of the electricity generated in Scotland is exported to ROUK by 2045.
- Electricity will be critical for Scotland's transition to Net Zero, being used to supply residential heating, industrial processes and transport. Hydrogen will also play a key role, particularly in industry and transport but also to supporting renewable generation.
- Hydrogen becomes increasingly important in supporting electric heating during peak demand periods as part of a hybrid hydrogen-heat pump system. It provides flexible heating and allows the heat pump to be more modestly sized to supply base load heat.
- Accelerated uptake of electric heating systems such as heat pumps is required to meet Scotland's ambitious near-term annual emissions reduction targets and non-statutory targets related to decarbonising residential heat.
- Biomass boilers can also be part of a low carbon heating sector in the 2020s and early-2030s but from the mid-2030s, biomass is more useful in hydrogen production. The role of bioenergy evolves throughout the pathways, steered by the presence of carbon capture and storage (CCS).
    - Pre-CCS time periods see bioenergy being used in heating to help speed up the decarbonisation of this sector and to produce biofuels to decarbonise transport (especially heavy-duty transport).
    - Once CCS becomes possible, biomass is diverted to applications that can deliver negative emissions. This is predominantly hydrogen production by gasification of biomass with CCS.
- One of the clearest observations common to all scenarios is the degree of technology uptake necessary to deliver a Net Zero transition. In particular, consumer technologies like heat pumps and electric or fuel-cell cars will need to be taken up en masse. These are technologies that will require significant capital investment. It is therefore clear that there needs to be careful consideration by decision makers across Government and the finance sector about how to enable the transition to be fair and affordable.
- Capital cost is not the only barrier to overcome. Some of these low/zero carbon technologies will require the breaking of old, and forming of new, habits and ways of doing things. For example, charging patterns and routines for EVs versus the current ad hoc approach to refilling with petrol or diesel; different kinds of financing or ownership models; or learning to operate heat pumps to maximise efficiency after a lifetime of experience with gas boilers.

Abbreviations list

ASHP	Air source heat pump
ATR	Auto thermal reformer
BECCS	Bioenergy with carbon capture and storage
CCC	Climate Change Committee
CCGT	Combine cycle gas turbine
CCS	Carbon capture and storage
CCPu	Climate change plan update
CEH	Centre for Ecology and Hydrology
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
DACCS	Direct air carbon capture and storage
EPC	Energy performance certificate
ESME	Energy systems modelling environment
EV	Electric vehicle
GGR	Greenhouse gas removal
GHG	Greenhouse gas
GSHP	Ground source heat pump
GW	Gigawatts ($1x10^6$ kW) – unit of power
HP	Heat pump
HDV	Heavy duty vehicle
HGV	Heavy goods vehicle
ICE	Internal combustion engine
OCGT	Open cycle gas turbine
PHEV	Plug-in hybrid electric vehicle
ROUK	Rest of UK
SMR	Steam methane reformer
TWh	Terawatt hour ($1x10^9$ kWh) – unit of energy

Contents

1. Introduction

1.1 Background

In 2019, Scotland set a target to achieve net zero emissions by 2045, one of the most ambitious national targets in support of climate change mitigation. This includes an interim target to reduce Scotland’s 2030 greenhouse gas (GHG) emissions by 75% compared to 1990. To support these targets, Scottish Government has set out a series of sector specific measures, collated and summarised in the 2020 Update to the Climate Change Plan (CCPu)[1]. A summary of the Scottish net zero policy landscape can be found in ‘Appendix I – Background Analysis’.

In this project, Scottish Government and the ClimateXChange (CXC) commissioned Energy Systems Catapult (ESC) to develop a set of Scotland-specific whole energy system scenarios. These scenarios demonstrate three qualitatively different routes for Scotland to meet its emissions reduction targets, allowing different choices and potential implications to be explored. A fourth, less ambitious scenario was also developed but this was unable to meet Scottish and UK greenhouse gas targets.

Scenario analysis

Scenario analysis is a key tool to aid decision-making under conditions of uncertainty. Energy system scenarios, conducted properly, can provide the basis for:

- **Comprehensive stakeholder engagement:** Scenarios are a popular way to encourage and facilitate participation from across academia, government, civil society, and business.
- **Collaborative learning and a shared vision**: A participatory approach ensures traditional siloes and preconceptions can be challenged, whilst respecting legitimate differences, so that a shared understanding of the problem space can be formed.
- **Public communication**: Since full public participation is usually impractical, scenarios provide an ideal basis for subsequently communicating the ‘big picture’ to a non-specialist audience.
- **Government strategy and policy analysis**: A set of off-the-shelf scenarios enables analysts from a range of policy areas to rapidly assess strategies against a range of diverse futures.
- **Consistency in future analysis**: Where subsequent deep dives are required to improve the treatment of specific issues (e.g., EV charge point rollout, Scottish industry clusters) a common set of national energy system scenarios can ensure consistency across these.
- **Regular updates**: When planned and delivered well, scenarios can be an iterative process ensuring all the above benefits can be captured on an ongoing basis (e.g., biannually).

Specifically, in the context of Net Zero, energy system scenarios can help identify no/low-regret technologies for achieving emissions reductions. From a Governmental perspective, scenarios can be particularly key where strategic choices will have to be made in relation to critical infrastructure.

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[1] https://www.gov.scot/publications/securing-green-recovery-path-net-zero-update-climate-change-plan-20182032/

1.2 Project Approach and Evidence Base

Figure 1.1 provides a schematic overview of the methodological approach applied in developing these scenarios – further explanation is provided below:

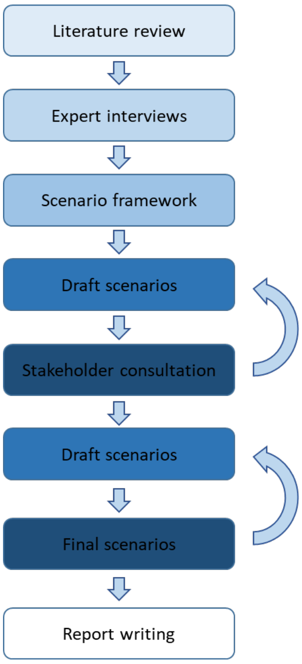

Figure 1.1: Schematic overview of the methodological approach

Literature review: A review of Scottish energy scenarios and relevant reports was conducted using a framework devised to ensure the systematic collection of features such as: methodology, inputs, outputs, and findings. The review also provided a synthesis of commonalities and differences across the literature. See 'Appendix I – Background Analysis' for a literature review summary.

Expert Interviews: A series of semi-structured interviews were conducted with the authors of key studies identified in the literature review; experts from Scottish Government; and other key stakeholders Acknowledgements. These were used to better understand issues identified in the literature review and develop key areas of the scenario design.

Proposed Scenario Framework: Informed by the literature review and expert interviews, we developed a scenario framework proposal for the Scottish Government Steering Group and external peer review. This set out the overall framework, the rationale and an outline of the individual scenarios proposed, showing how key themes could be explored. Themes included:

- Socio-economic trends and energy service demands.
- Availability, cost, and performance of key technologies.
- Strategic infrastructure choices such as heating.

This proposal was reviewed by the Scottish Government project team (including CXC), the Steering Group, and by our external peer reviewer, Professor Gareth Harrison.

Draft Scenarios: Following feedback on the proposed scenario framework, a first draft set of scenarios was developed. For each of the four scenarios, a table of assumptions was built up with reference to Scottish Government policy targets and the wider literature. Once agreed, these were scripted into our whole system energy model (Energy System Modelling Environment (ESME) – see Box 1 right) and initial results generated.

As part of an iterative process, these results were reviewed with the Scottish Government project team and refined until a completed first draft set of scenarios were reached and shared with the Steering Group and external peer reviewer.

Box 1: Energy Systems Modelling Environment

ESME was developed to evaluate the role of innovation in UK energy system decarbonisation, from energy resources and conversion through to end use in buildings, transport and industry. It is used by ESC, Government, industry, the Climate Change Committee and academia.

ESME is an optimisation model and finds the least-cost combination of energy resources and technologies that satisfy UK energy service demands along the pathway to 2050. Constraints include emissions targets, resource availability and technology deployment rates, as well as operational factors that ensure adequate system capacity and flexibility.

Importantly, ESME includes a multi-regional UK representation and can assess the infrastructure needed to join up resources, technologies and demands across the country. This includes transmission and distribution networks for electricity and gas, and pipelines and storage for CO_2. This feature of ESME means we have been able to evaluate decarbonisation pathways for Scotland within in the wider context of UK climate change policy. Specifically we are able to delve into the interactions between Scotland and the rest of the UK including flows of electricity and hydrogen.

Stakeholder consultation: The draft scenarios were presented in summary form at an invited workshop of key stakeholders across sectors, as well as shared with the Steering Group and external peer reviewer. More comprehensive documentation was then sent out to these participants, along with a structured set of consultation questions.

Final scenarios: Combining steering group, peer review and stakeholder consultation feedback, the assumption sets for each of the four scenarios were revised in agreement with Scottish Government. A fresh set of modelling runs were generated, and further refinements agreed until a final set of scenarios were reached.

Report writing: With the scenario modelling runs completed, quantitative charts and qualitative narratives were generated, and key insights and discussion points extracted. The subsequent analysis in this Final Report is here to help inform policy but not set it.

2. Scenarios

Four scenarios have been developed to explore a range of possible, but distinct, pathways, distinguished by different policy choices and technological and behavioural change characteristics. Each sought to achieve Scotland’s 2030 and 2045 emissions reduction target, as well as annual interim targets. They were commissioned to inform thinking, encourage debate, and evaluate options.

The scenarios are not fixed policy pathways, mutually exclusive or an exhaustive list that Scotland should follow to meet greenhouse gas (GHG) targets. Nor do they provide specific solutions to the net zero transition. They represent but a handful of points from a near-infinite pool of possible options. However, by defining distinct points within this pool, each with interesting features, we can generate debate and explore the implications of certain choices and options.

Scenarios and scenario analysis using models like ESME are just one tool available to help unpick the challenges and identify the opportunities of decarbonisation. **This analysis is conducted through a single, techno-economic lens and therefore should form just part of the wider analysis, including, amongst other things industrial policy and ambitions for a ‘Just Transition’.**

Importantly for this analysis, ESME has allowed us to identify three potential pathways which can meet Scotland’s decarbonisation targets, nested in and consistent with the wider UK energy system and decarbonisation targets. Whilst not the focus of this analysis, the interaction between the different decarbonisation targets within the UK, from a policy point of view will be an interesting area for further consideration.

2.1 Scenario framework

The scenarios have been devised using a two-by-two matrix framework with the key dimensions of technological innovation and societal change on each axis. Figure 2.1 shows the position of the four scenarios on this framework.

2.1.1 Technological innovation

In this framework, technology innovation refers to the extent of innovation in a number of key technologies important for net zero. This increases the availability of key technologies within ESME. They include:

- Carbon dioxide (CO_2) removal (e.g., direct air carbon capture and storage (DACCS)).
- Development of a domestic supply chain of biomass.
- Technology capacity in line with relevant non-statutory targets outlined in Scottish Government net zero policy landscape

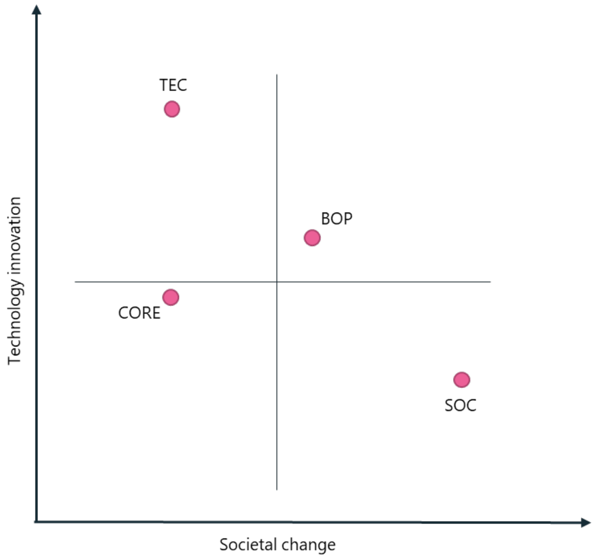

Figure 2.1: Scenario framework used in the analysis showing the position of the scenarios in relation to technology innovation and societal change

These advances result in a Scottish energy system characterised by the ability to remove CO_2 from the air; produce a high amount of biomass; and deploy large quantities of renewable generation, amongst other things.

2.1.2 Societal change

Societal change refers to the ability and willingness of the population to adopt behaviours more consistent with the net zero transition. This includes:

- Reducing demand for energy end uses such as heating and transport.
- Consuming less red meat and dairy.
- Preferences for nature-based removal of GHGs.

These behavioural changes result in a Scottish energy system characterised by reduced energy demand; lower emissions from farming; and greater reforestation/afforestation and peatland restoration.

2.1.3 Adoption of low/zero carbon technologies in ESME

Low and zero carbon technologies (e.g. heat pumps) are fundamental to meeting GHG targets. Since all the scenarios are aiming to meet GHG targets, there is an implicit assumption that industry and consumers will adopt new technologies. However, the rate of uptake is not included in either the technology innovation or societal change assumptions. Instead, the necessary rate of uptake to meet the decarbonisation targets, is largely determined by the model. This is useful in demonstrating the scale of the challenge associated with decarbonising different parts of the energy system. It encourages thought about who there will be implications for e.g. industry, business or consumers/homeowners.

2.1.4 Scenario overview

The framework outlined in Figure 2.1 allows us to explore different combinations of technological innovation and societal change:

- In the **lower left** quadrant of Figure 2.1, we have explored a scenario which sees less transformation in social attitudes and behaviours, reflecting a 'lifestyle-as-usual' approach to high emitting activities. Similarly, while the energy system undergoes significant technological change, the scenario assumes only modest innovation in key net zero technologies. Consequently, it is more difficult, potentially impossible, to meet Scotland's carbon targets. The '**CORE'** scenario developed for this project is one point within this quadrant and represents a scenario in which emission target are missed.

- Moving to the **lower right** quadrant, we explore a scenario with a greater societal willingness to adapt behaviours around high emitting activities. As a result, we see slower growth in aviation, greater reduction in red meat and dairy consumption, and increased afforestation because of a drive for increased green spaces. The 'Societal Change' ('**SOC'**) scenario developed for this project is one point within this quadrant.
- In the **upper left** quadrant, a focus on innovation ensures that a range of technological approaches can deliver emissions offsets, including through direct air carbon capture and high biomass production. The 'Technology' ('**TEC**') scenario developed for this project is one point within this quadrant.
- In the **upper right** quadrant, a mix of these behavioural and technological solutions offers a more balanced path to achieving the emissions targets. The 'Balanced Options' ('**BOP**') scenario developed for this project is one point within this quadrant.

Section 2.2 Scenario summaries provides a detailed explanation of the assumptions underpinning each scenario, as well as a more comprehensive narrative around the characteristics of each scenario.

2.1.5 Scenario feasibility

There are an infinite number of scenarios that can be positioned anywhere on the framework. Feasible scenarios will meet GHG targets, whilst infeasible ones will not – the boundary is show as a dotted line in Figure 2.2. There will be scenarios with different combinations of technology innovation and societal change that lie along the boundary between feasibility and infeasibility.

Scenarios with more technology innovation and/or more societal change than these borderline scenarios will likely meet the GHG targets and will occupy an area on the framework called the feasible region. Scenarios lacking sufficient technology innovation and/or societal change will fall within the infeasible region.

The TEC, BOP and SOC scenarios are three such possible pathways that are positioned in the feasible region (Figure 2.2). The CORE scenario is falls into the infeasible region – it failed to meet GHG targets because the level of technology innovation and societal change is not sufficient to mitigate GHG emissions.

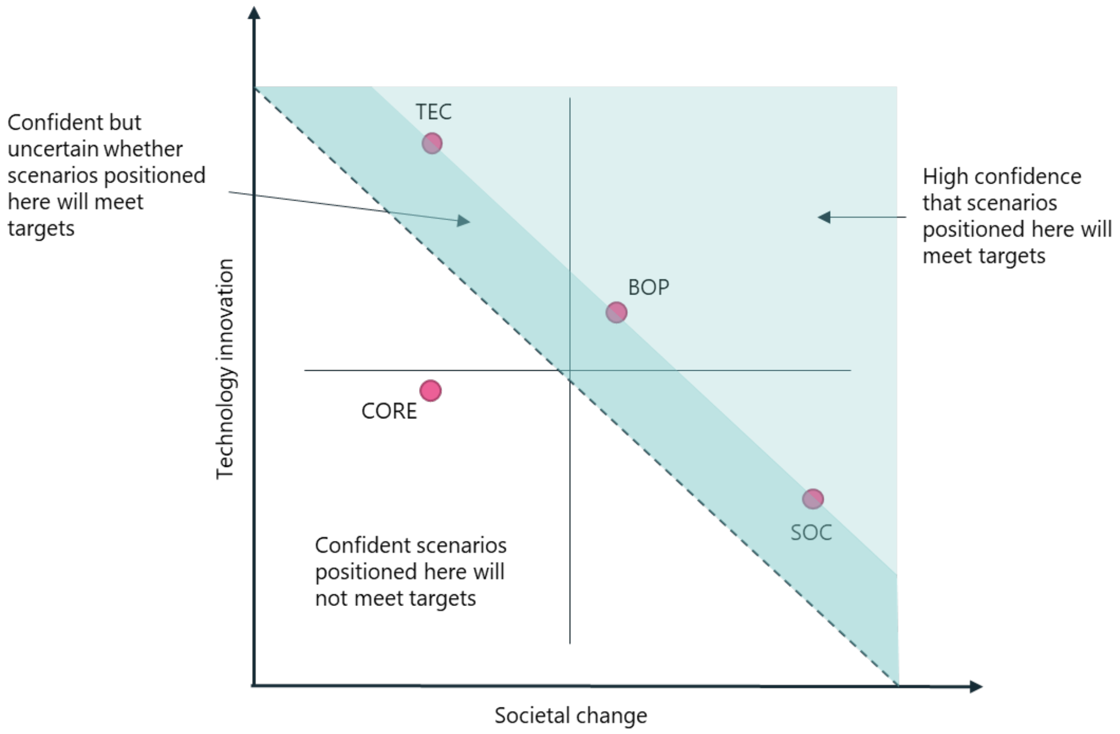

Figure 2.2: Illustration of the feasible and infeasible regions of the scenario framework.

It is not known how close the TEC, SOC and BOP scenarios are to the infeasible region. Therefore, the darker shaded area designating an uncertain feasible region could be narrower or a different shape entirely. It is only there to show the possibility that there are scenarios less ambitious (relative to these three scenarios) in technology innovation or societal change that could still meet targets.

2.2 Scenario summaries

This section provides a more comprehensive narrative for each of the scenarios and calls out the key assumptions underpinning them. Key assumptions common to all scenarios are also noted in the final sub-section of this section[2].

2.2.1 Technology ('TEC') narrative

Innovation in technology helps to deliver zero carbon energy and GHG removals.

Under this scenario several key features have been constrained in the modelling to represent real-world events such as the ScotWind auction:

- The maximum capacity put forward in the ScotWind auction for offshore wind (25GW) is built on top 11GW of non-ScotWind capacity, and 20GW of onshore wind – this generates the majority of the electricity in Scotland. All electricity generated enters the GB grid. In reality will increase network reinforcement needs across Scotland, which are not well captured in ESME with relatively coarse spatial representation. It should be noted that other scenarios will be possible in which electricity is stored in batteries or converted to hydrogen.

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[2] It should be noted that the CORE scenario is not detailed beyond this point in the report, as the limitations on technological advances and societal behaviour change, mean that it cannot achieve the decarbonisation targets.

- Scotland becomes the first country in the UK to deploy a commercial-scale direct air carbon capture and storage (DACCS) plant. Engineered removal of CO_2 reaches 2mtCO_2/yr. in Scotland by 2040. A well-established carbon capture and storage network enables industrial decarbonisation and bulk hydrogen production.
- Due to this CCS infrastructure and proximity to CO_2 storage sites in the North Sea, Scotland becomes an important producer of hydrogen, meeting its own needs as well as supplying the rest of the UK (ROUK)
- Innovative practices and policies support the establishment of a domestic biomass supply chain in Scotland, which yields 25TWh/yr. of primary energy by 2045. Biomass is used in conjunction with CCS from 2035 to produce hydrogen, electricity and negative emissions.
- Engineered removals and negative emissions from bio-energy carbon capture and storage (BECCS) mean the impact of the net zero transition on people's lives is relatively modest. The average temperature in homes continues to rise to around 21°C by 2050 as people's perception of thermal comfort evolves.
- People also continue to travel mainly by car, albeit electric ones, and there is still demand for flights abroad. Whilst veganism and vegetarianism become more popular, people continue to eat red meat and dairy products.

2.2.2 Technology ('TEC') assumptions

The key assumptions for the TEC scenario are included below in Table 2.1.

Table 2.1: Summary of key 'Technology' scenario assumptions

Assumption	Type	Description	Rationale
Commercial scale DACCS plant by 2030	Engineered GGR	1mtCO_2/yr. capture plant by 2030 increasing to 2mtCO_2/yr. by 2040	Conservative estimate developed in consultation with the Scottish Government
High Scottish biomass supply	Engineered GGR	25TWh/yr. biomass produced by 2045, up from approx. 7TWh/yr. today 5.2TWh/yr. imported biomass 2020-50	ESME high biomass supply assumption. CCC assumption on imported biomass
High Offshore wind capacity	Technology	11GW by 2030 in line with upper end of range outlined in Scottish Government policy statement. Plus 25GW by 2045 as part of ScotWind auction. Total capacity 36GW in 2045	Scottish Government policy statement
High Onshore wind capacity	Technology	20GW by 2030 in line with upper end of range outlined in Scottish Government policy statement	Scottish Government policy statement
Zero emission HGVs	Technology	New HGVs to be zero emission from 2035	Scottish Government policy statement
BECCS availability	Engineered GGR	First deployment of bioenergy with CCS 2035	Estimate, based on TRLs and construction/supply chain lead-in times

Boiler set point temp. 21°C	Societal change	Boiler set point temperatures rise to average of 21°C by 2050 from around 19°C in 2020	ESME Reference demand case
Slow switch from gas boilers	Technology	The switch away from gas boilers for heating homes and non-domestic buildings is slowed down	Developed in consultation with the Scottish Government to test the impact of slower switch from natural gas in homes/non-domestic buildings
Afforestation	Nature-based GGR	UK planting rates: 30,000 hectares by 2025; 50,000 hectares between 2030 and 2050	In line with CCC's Widespread Innovation scenario delivering 6mtCO_2e savings in Scotland in 2045
Peatland restoration	Nature-based GGR	Peat extraction remains at 2014 levels. 250 kha of peatland (40% of currently degraded peatland) restored by 2030. (Scottish Government, 2017). Restored peatland is assumed to be upland peat and forest.	In line with CEH central scenario
Diet	Societal change	20% by 2050 for all meat and dairy; all replaced with plant based.	In line with CCC's Headwinds scenario

2.2.3 Balanced Options ('BOP') narrative

Balanced adoption of societal change and technological solutions.

Under this scenario several key features have been constrained in the modelling:

- 15GW of the ScotWind auction capacity is built along with an additional 8GW of non-ScotWind capacity and 16GW of onshore wind. All electricity generated enters the GB grid. Similar considerations around grid reinforcement needs and alternative avenues for electricity (e.g. into hydrogen production) as mentioned in TEC apply in BOP.
- A commercial scale DACCS plant is built in the mid-2030s but remains the only one in operation throughout the pathway removing 1mtCO_2/yr.
- Biomass supply in Scotland is 21TWh/yr. by 2045. Biomass is used in combination with CCS from 2035 to produce electricity and hydrogen whilst delivering negative emissions.
- There is more effort by people to reduce their carbon footprint and energy consumption by changing to a more plant-based diet, adopting behaviours and strategies to reduce demand for heat (e.g. smart controls or turning down thermostat temperatures) and avoiding car travel where possible.

2.2.4 Balanced Options ('BOP') assumptions

The key assumptions for the BOP scenario are included below in Table 2.2.

Table 2.2: Summary of key 'Balanced Options' scenario assumptions

Assumption	Type	Description	Rationale
Commercial scale DACCS plant by 2030	Engineered GGR	1mtCO$_2$/yr. capture plant by 2030 remaining at 1mtCO$_2$/yr. by 2040 0.5mtCO$_2$/yr. capture plant by 2030 increasing to 1mtCO$_2$/yr. by 2040	Conservative estimate developed in consultation with the Scottish Government
Central Scottish biomass supply	Engineered GGR	21TWh/yr. biomass produced by 2045, up from approx. 7TWh/yr. today 5.2TWh/yr. imported biomass 2020-50	ESME central biomass supply assumption. CCC assumption on imported biomass
Central Offshore wind capacity	Technology	8GW by 2030 in line with lower end of range outlined in Scottish Government policy statement. Plus 15GW by 2045 as part of ScotWind auction. Total capacity 23GW in 2045	Scottish Government policy statement
Central Onshore wind capacity	Technology	16GW by 2030 in line with lower end of range outlined in Scottish Government policy statement	Scottish Government policy statement
Zero emission HGVs	Technology	New HGVs to be zero emission from 2040	UK Government policy statement
5mt captured CO$_2$ in 2030	Engineered GGR	No more than 5mtCO$_2$ captured from DACCS and CCS (power and industry) before 2030	Upper limit developed in consultation with Scottish Government
BECCS availability	Engineered GGR	First deployment of bioenergy with CCS 2035	Estimate, based on TRLs and construction/supply chain lead-in times
Boiler set point temp. 20°C	Societal change	Boiler set point temperatures rise to average of 20°C by 2050 from around 19°C in 2020	Part way between TEC and SOC
No new gas boilers	Technology	No new gas boilers from 2030	New homes use zero emission heating system from 2025

			Decarbonise 1m on gas homes and 50,000 non-domestic buildings
District heat networks[3]	Technology	At least 6TWh heat supplied by district heat networks in 2030	Scottish Government policy statement
Afforestation	Nature-based GGR	UK planting rates: 30,000 hectares by 2025, 50,000 hectares between 2035 and 2050	In line with CCC's Balanced Pathway scenario delivering 4mtCO$_2$e savings in Scotland in 2045
Peatland restoration	Nature-based GGR	Cessation of peat extraction with 50% restoration by 2050. 25% area restoration of degraded lowland peat, restoration of 50% of area of degraded upland peat.	In line with CEH low scenario
Diet	Societal change	20% by 2030 for all meat 35% for all meat by 2050; 20% by 2030 for dairy then flatlined to 2050; all replaced with plant based	In line with CCC's Balanced Pathway scenario

2.2.5 Societal Change ('SOC') narrative

Societal engagement leading to shifts in behaviour to reduce energy consumption and GHG emissions.

Under this scenario several key features have been constrained in the modelling:

- The people of Scotland are engaged with the climate agenda, adopting low carbon lifestyles to reduce both the demand for energy and GHG emissions. For example:
    - People walk and cycle more rather than using the car and take fewer flights abroad.
    - Average temperature in homes rises to just 19.5°C by 2050 (from around 19°C in 2020) as people change their attitude towards thermal comfort and/or adopt smart heating controls.
    - Vegan and vegetarian diets become mainstream with a significant shift away from red meat and dairy.

  All these things not only reduce energy consumption and carbon footprints but improve people's health and wellbeing.
- There are no engineered removals of CO$_2$, CCS rollout is limited and BECCS does not get established at commercial scale until the early 2040s.
- There is less reliance on biomass to deliver negative emissions with no biomass being imported to Scotland and domestic supply limited to 12TWh in 2045 (from around 7TWh today).

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[3] The BOP scenario was required to meet the district heat statutory target. However, model constraints were not needed to ensure this happened. Instead, it was a natural model decision to supply more than 6TWh of heat from DHNs in 2030.

- Low carbon diets combined with an ambitious programme of tree planting and peatland restoration mean land use becomes a net sink of CO_2 by 2040.

2.2.6 Societal Change ('SOC') assumptions

The key assumptions for the SOC scenario are included below in Table 2.3.

Table 2.3: Summary of key 'Societal Change' scenario assumptions

Assumption	Type	Description	Rationale
Low Scottish biomass supply	Engineered GGR	12TWh/yr. biomass produced by 2045, up from approx. 7TWh/yr. today No imported biomass 2025-50	Minimum viable amount of biomass producing feasible solution
Zero emission HGVs	Technology	New HGVs to be zero emission from 2040	UK Government policy statement
2.5mt captured CO_2 in 2030	Engineered GGR	No more than 2.5mtCO_2 captured before 2030	Upper limit developed in consultation with Scottish Government
BECCS availability	Engineered GGR	First deployment of bioenergy with CCS 2040	Estimate, based on TRLs and construction/supply chain lead-in times
Boiler set point temp. 19.5°C	Societal change	Boiler set point temperatures rise to average of 19.5°C by 2050 from around 19°C in 2020	In line with ESC's Patchwork scenario
No new gas boilers	Technology	No new gas boilers from 2030	New homes use zero emission heating system from 2025 Decarbonise 1m on gas homes and 50,000 non-domestic buildings
Afforestation	Nature-based GGR	UK planting rates: 30,000 hectares by 2025; 50,000 hectares by 2030 and 70,000 hectares between 2035-2050	In line with CCC's Widespread Engagement scenario delivering 5mtCO_2e savings in Scotland in 2045
Peatland restoration	Nature-based GGR	Cessation of all peat extraction with 100% restoration by 2030. 50% area restoration of degraded lowland peat, 75% area restoration of degraded upland peat; restoration of 50% of forest area planted on peat since 1980	In line with CEH stretch scenario
Diet	Societal change	20% by 2030 for all meat and dairy; 50% by 2050; all replaced with plant based.	In line with CCC's Widespread Engagement scenario

2.2.7 Common scenario assumptions

Several assumptions have also been made for all scenarios – these are detailed below in Table 2.4.

Table 2.4: Summary of key assumptions common to all scenarios

Assumption	Type	Description	Rationale
Peterhead CCGT	Technology	Unabated CCGT plant at Peterhead ceases operation by 2030	Estimated retirement date pre-2030
Unabated fossil for power	Technology	No new unabated fossil-based power generation	Scottish Government policy statement
Legacy nuclear power	Technology	Existing plants at Torness and Hunterston cease operation	Hunterston ceased operation in Jan 22. Torness is due to cease operation end of 2028
New nuclear power	Technology	No new nuclear fission power generation	Scottish Government policy statement about existing fission technologies.
No new internal combustion engine cars & vans	Technology	No new ICE cars and vans from 2030 (also includes non-plug-in hybrids)	In line with UK Government legislation
No new hybrid cars and vans	Technology	No new plug-in hybrid cars and vans from 2035	In line with UK Government legislation
Limited BECCS/biomass use in industry	Technology	Biomass consumption in industry does not increase from 2020 and BECCS in industry is limited	Biomass is not expected to form a large part of the industrial fuel mix (beyond where it is already being used) therefore a limit was placed on it for the modelling (Element Energy, 2020)

3. Insights & discussion

This part of the report presents and analyses the pathways for the three scenarios that meet Scotland and the UK's decarbonisation targets. It is split into several sections: Decarbonisation pathways for Scotland; Supplying net zero energy; Greenhouse gas removals; Bioenergy; The role of natural gas; Meeting energy end-use demand; and Costing the transition.

Decarbonisation pathways for Scotland provides an overview of the overarching scenario characteristics, followed by a high-level analysis of the rate of decarbonisation by sector (i.e. power, transport, heating and industrial); an assessment of primary resource consumption; and a summary of the pathways to net zero.

'Supplying zero carbon energy' takes a deeper look at electricity generation, capacity, and imports/export to the ROUK and hydrogen production. 'Greenhouse gas removals' looks at the role of engineered and nature-based solutions in removing and capturing carbon. The Bioenergy and the role of natural gas sections look at the roles of these energy vectors in the transition. Meeting energy end use demand delves into which sectors consume electricity and hydrogen and how the end uses of heating, transport and industry are decarbonised. Finally, Costing the transition provides high level analysis of the costs associated with the three modelled scenarios.

3.1 Decarbonisation pathways for Scotland

3.1.1 Overarching scenario characteristics

Technology scenario

TEC is characterised by higher demands for energy end uses (e.g. in industry, transport and residential heating). Whilst there is a high uptake of zero carbon technologies in each of the main energy system sectors, residual emissions from transport and industry remain higher than in the BOP and SOC scenarios.

Higher availability of biomass and GHG removal technologies (i.e. CCS and DACCS) allows more CO_2 removal within the TEC scenario than SOC and BOP. This creates some flexibility around decarbonisation choices in the energy system.

Balanced Options scenario

BOP is positioned somewhere between TEC and SOC in terms of emissions and removals. Energy end-use demands are somewhat tempered by a degree of behavioural shift adopted across society to reduce reliance on cars for private travel and limit the increase in average internal temperature in homes from now until 2045. Smart heating controls and strategies are one way in which people can keep average temperature in the home down without compromising on comfort.

There is also a shift away from red meat and dairy products towards plant-based alternatives. However, this diet shift is not taken as far as in the SOC scenario. Peatland restoration and afforestation is also less ambitious than in SOC, so land use remains a net source of GHG emissions. Engineered removals and BECCS offset remaining emissions from industry, transport and residential heat and land use in the 2040s.

Societal Change scenario

SOC is characterised by lower energy demand but also less ability to remove CO_2 from the atmosphere (i.e. delayed CCS, low biomass availability and no engineered removals). Because there is less ability to remove CO_2 from the system, there is more of an emphasis on minimising emissions from each of the sectors through adoption of zero carbon technologies.

Despite limited engineered CO_2 removal options, savings are made from the land use sector which becomes a net sink of CO_2 by 2040. This is due to a combination of an ambitious programme of peatland restoration and afforestation, and a greater societal shift away from conventionally produced red meat and dairy products relative to TEC and BOP.

3.1.2 Possible pathways to Net Zero Scotland

The three Net Zero compliant scenarios analysed in this report represent three possible pathways for Scotland to reach net zero. The purpose of this exercise is not to prescribe a particular set of policy decisions, but to explore what different policy decisions, in combination with broader background developments in technology and behavioural change, might drive. Figure 3.1, 3.2 and 3.3 summarise in parallel and through time, the key modelled assumptions (‘Scenario framework assumptions’) from Table 2.1- 2.4 and the system choices made by ESME for each modelled scenario (‘Modelled pathway choices’).

Examination of the pathway for each scenario highlights the challenges that would need to be addressed, decisions that would need to be taken and policy enablers that would need to be put in place. These pathways are intended to structure and stimulate further debate. Decisions will not be taken purely on a techno-economic, or an energy system only basis, or on the basis of a single model/modelling exercise.

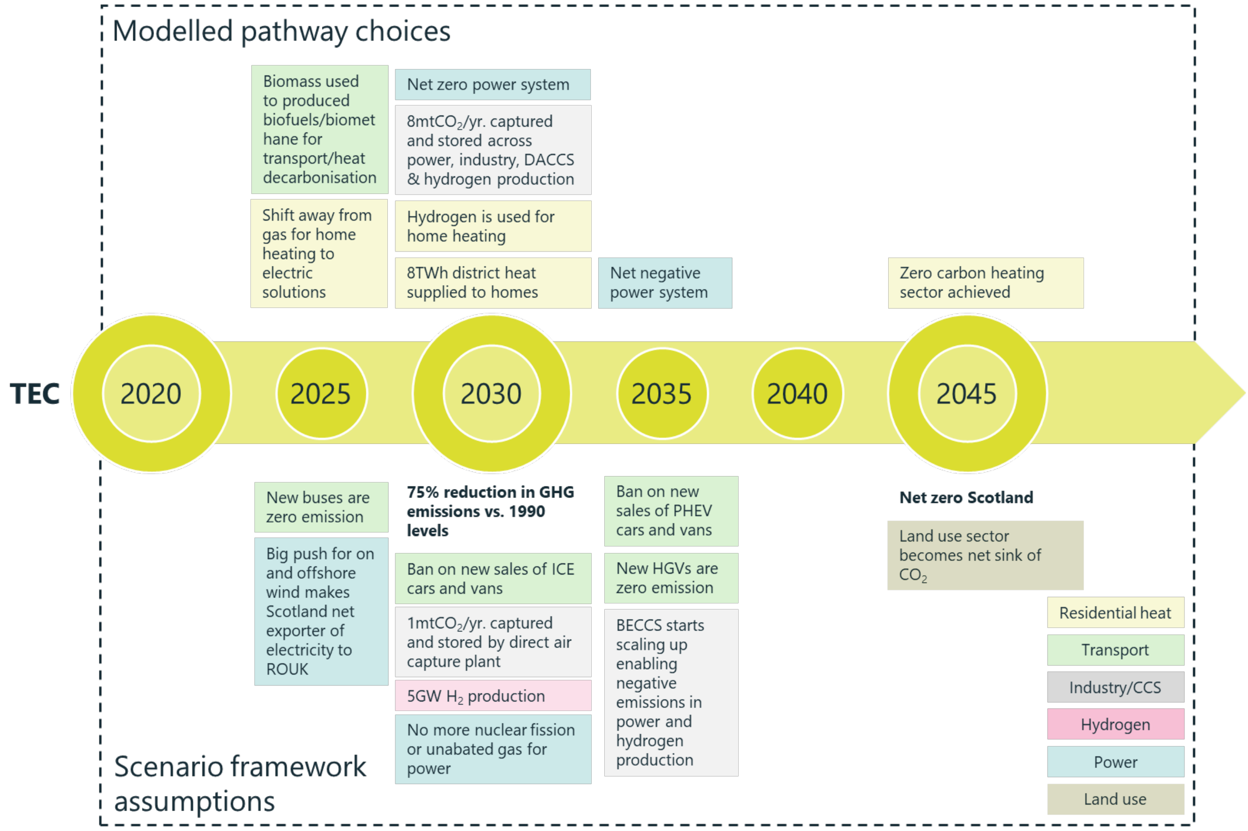

Figure 3.1: Technology pathway

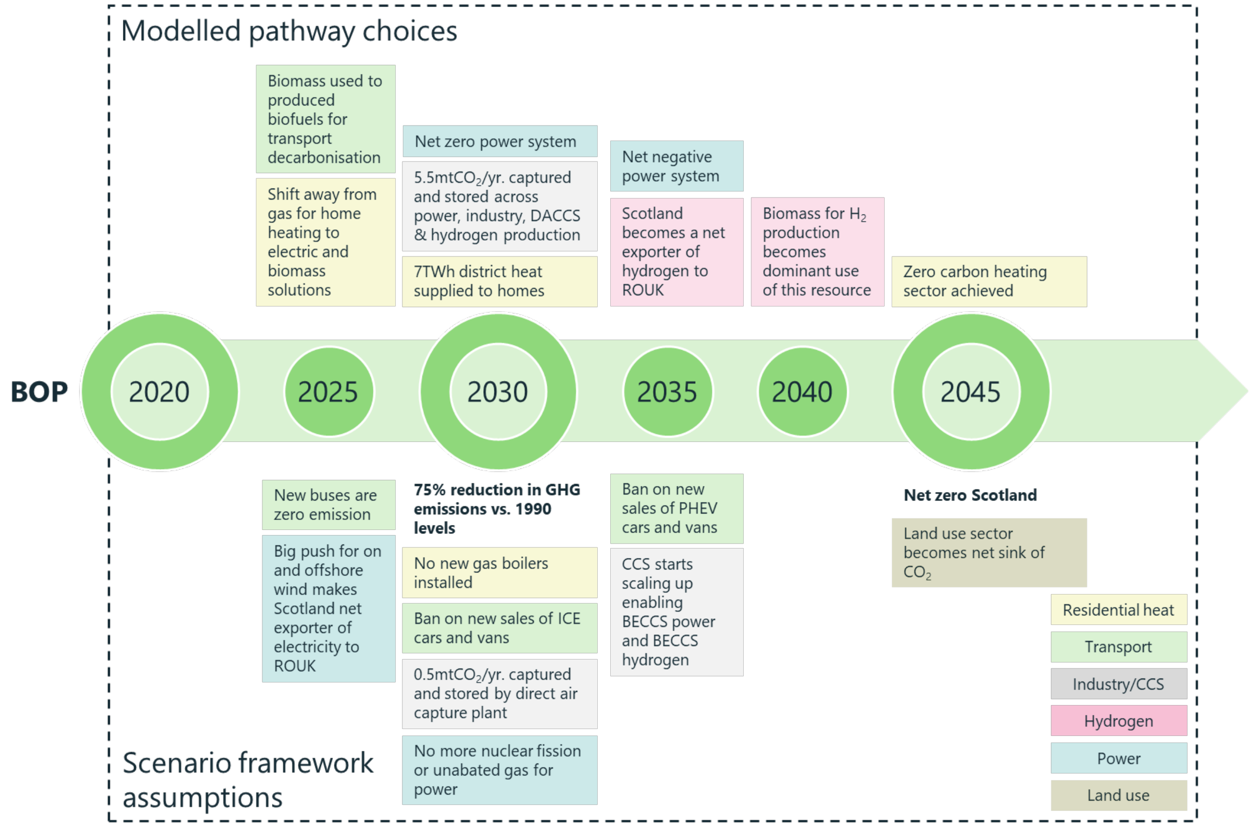

Figure 3.2: Balanced Options pathway

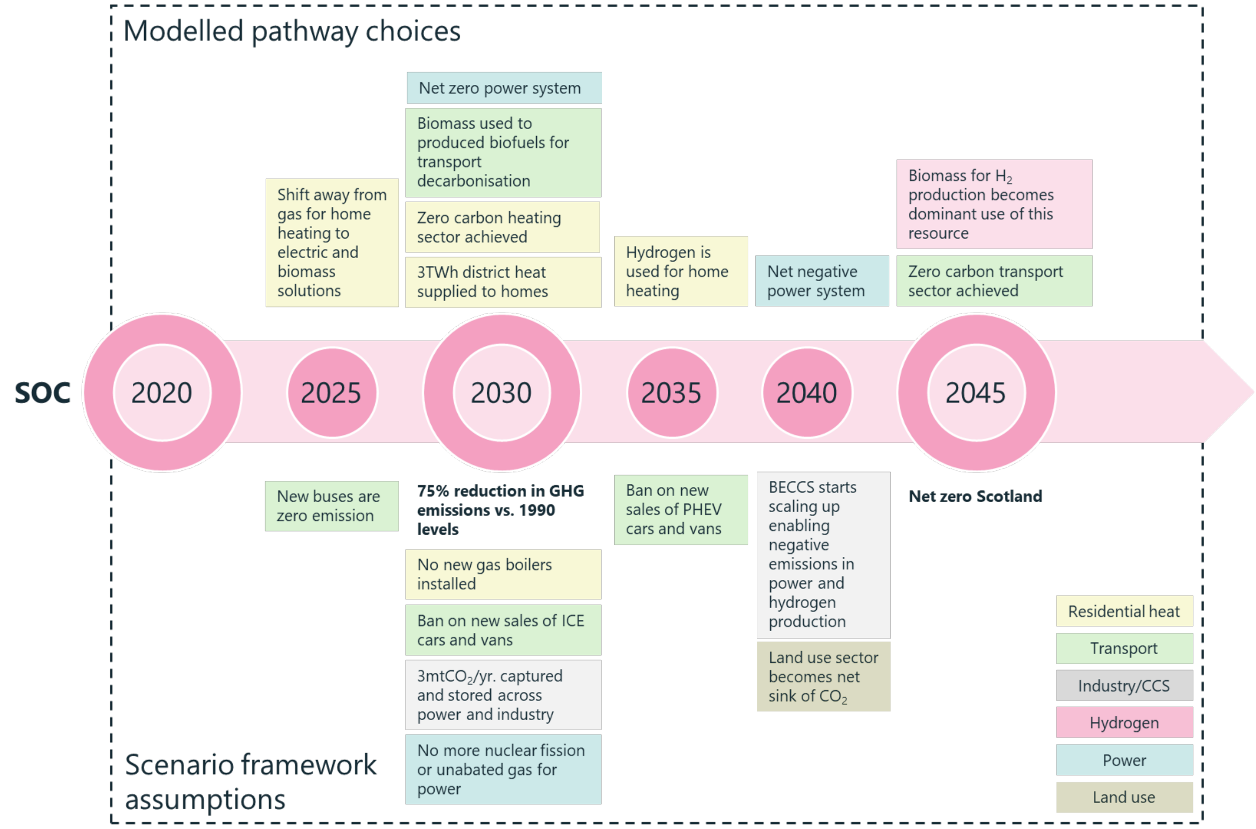

Figure 3.3: Societal Change pathway

3.1.3 Rate of decarbonisation by sector

The rate of decarbonisation in Scotland in each of the scenarios is demonstrated in Figure 3.4 which shows the net greenhouse gas emissions emanating from the main energy system and land use sectors.

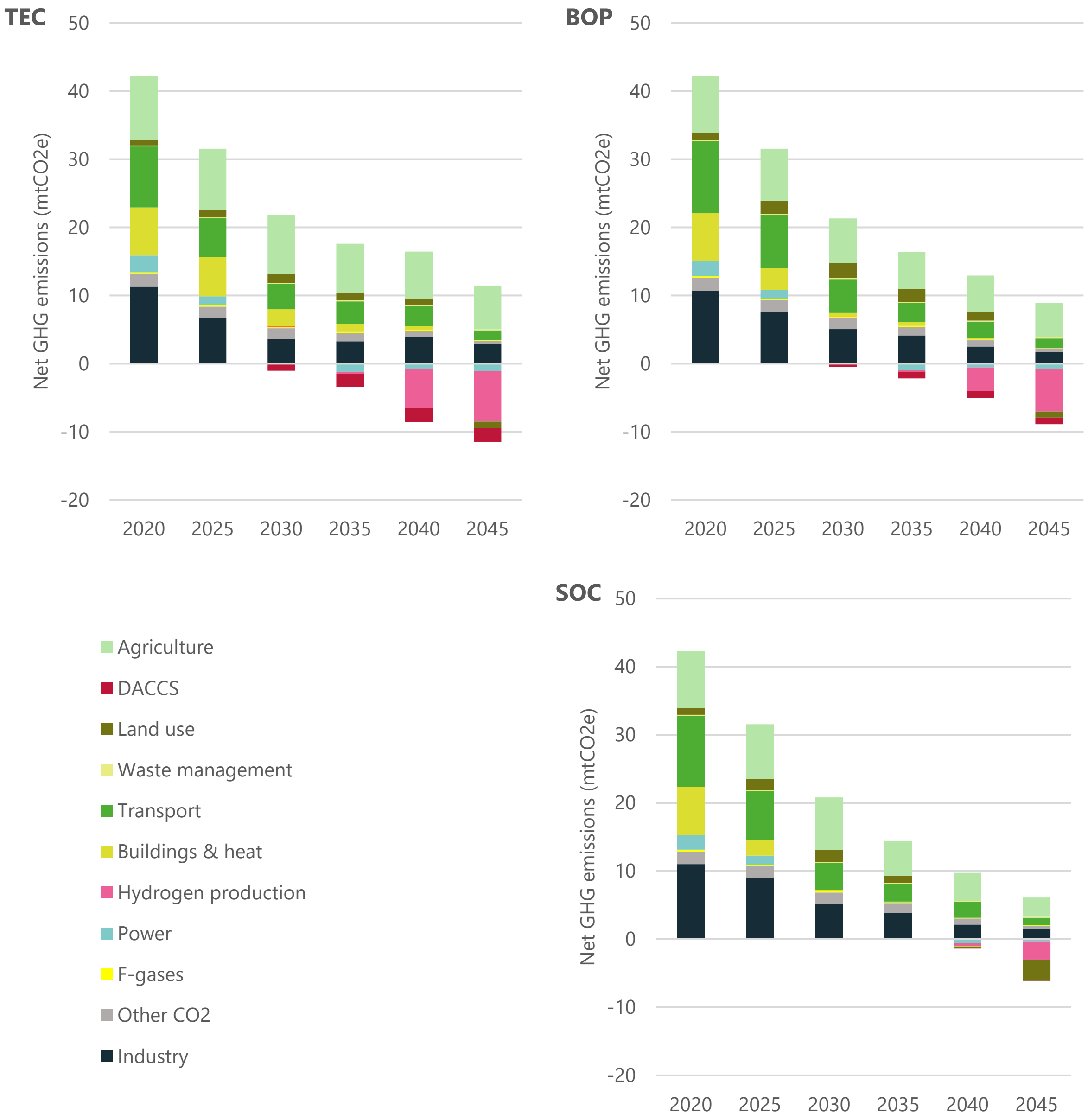

Figure 3.4: Net greenhouse gas emissions in Scotland broken down by sector for each scenario. Note that 2020 is a modelled year in ESME and uses a pre-COVID estimate of energy demand

Table 3.1 summarises the key developments for the key sectors: power, heating, transport and industry.

Table 3.1: Summary of the rate of decarbonisation by sector

Sector	Description
Power	The power sector decarbonises quickest becoming net zero by 2030 in all scenarios and becomes net negative post-2030 – this occurs in 2035 in TEC and BOP and 2040 in SOC. Decarbonisation by 2030 is largely driven by the retirement of the Peterhead CCGT, which is a constraint in all three scenarios. In the 2030s, BECCS for power delivers a net negative power system in TEC and BOP. As a result of slower deployment of CCS assumed in SOC, ability to roll out commercial scale BECCS in power delays net negativity until 2040.
Heating	Residential heat decarbonises next becoming almost zero carbon by 2030 in BOP and SOC. There is a shift from natural gas as the dominant supplier of residential heat to a combination of three main zero carbon energy vectors: electricity, hydrogen and district heat. The switch from natural gas in TEC is slower and accounts for higher emissions in this sector vs. the other scenarios. Nevertheless, some decarbonisation of gas occurs as biomass is used to produce biomethane. Biomass also plays an important role in the near-to-mid-term providing homes with low carbon heat until the mid-2030s. In BOP and SOC biomass is used directly in biomass boilers. Some of these are pre-existing and will need replacing by 2030. However, some are installed after 2020 and will need replacing in the mid-2030s. In reality, households would not be expected to switch to and then from biomass boilers given the cost and disruption. In TEC, gas boiler switching is delayed, and biomass is used to produce biomethane to decarbonise the gas supplied to homes. From the mid-2030s, the role of biomass shifts as CCS options begin to appear allowing power and then hydrogen to be produced from BECCS plants. Hydrogen produced from BECCS plants delivers both negative emissions as well as a zero-carbon energy vector that can supply flexible heat.
Transport	Transport sector is next to decarbonise with the 2030 national ban on new ICE car and van sales applied to all scenarios. Five years later, a similar ban is applied to plug-in hybrid cars and vans. SOC car travel becomes almost entirely electrified by 2035 but emissions from heavy duty vehicles remain. By 2045, SOC land transport sector is practically zero carbon thanks to uptake of zero carbon vehicles and active travel modes (away from car use). TEC and BOP see some residual plug-in hybrid cars on the road up to 2040 and land transport remains a net emitter of GHG in 2045. Passenger rail is decarbonised by 2035 in all three scenarios. This is achieved through electrification (although in reality other options exist). Ammonia/hydrogen-fuelled ships reach commercial scale deployment levels by 2045 and lead to significant decarbonisation of the shipping sector in TEC, BOP and SOC. Aviation continues to emit throughout each of the pathways although old aircraft are retired for those with improved fuel efficiencies.

Industry	Industrial emissions decrease steadily over time in all scenarios as industries switch from fossil fuels to electricity and hydrogen. Industrial emissions fall further in SOC because it is a low energy demand scenario.

3.1.4 Primary resource consumption in Scotland

Fossil fuels and renewable sources of energy along with nuclear fuel all represent primary resources used in the Scottish energy system. If energy generated in Scotland is not utilised in Scotland, then the primary resource consumption to support that generation is not attributable to Scotland. Likewise, any resources used in other parts of the UK to export energy vectors utilised in Scotland are attributable to Scotland. Figure 3.5 shows the primary resource consumption for Scotland for the three scenarios.

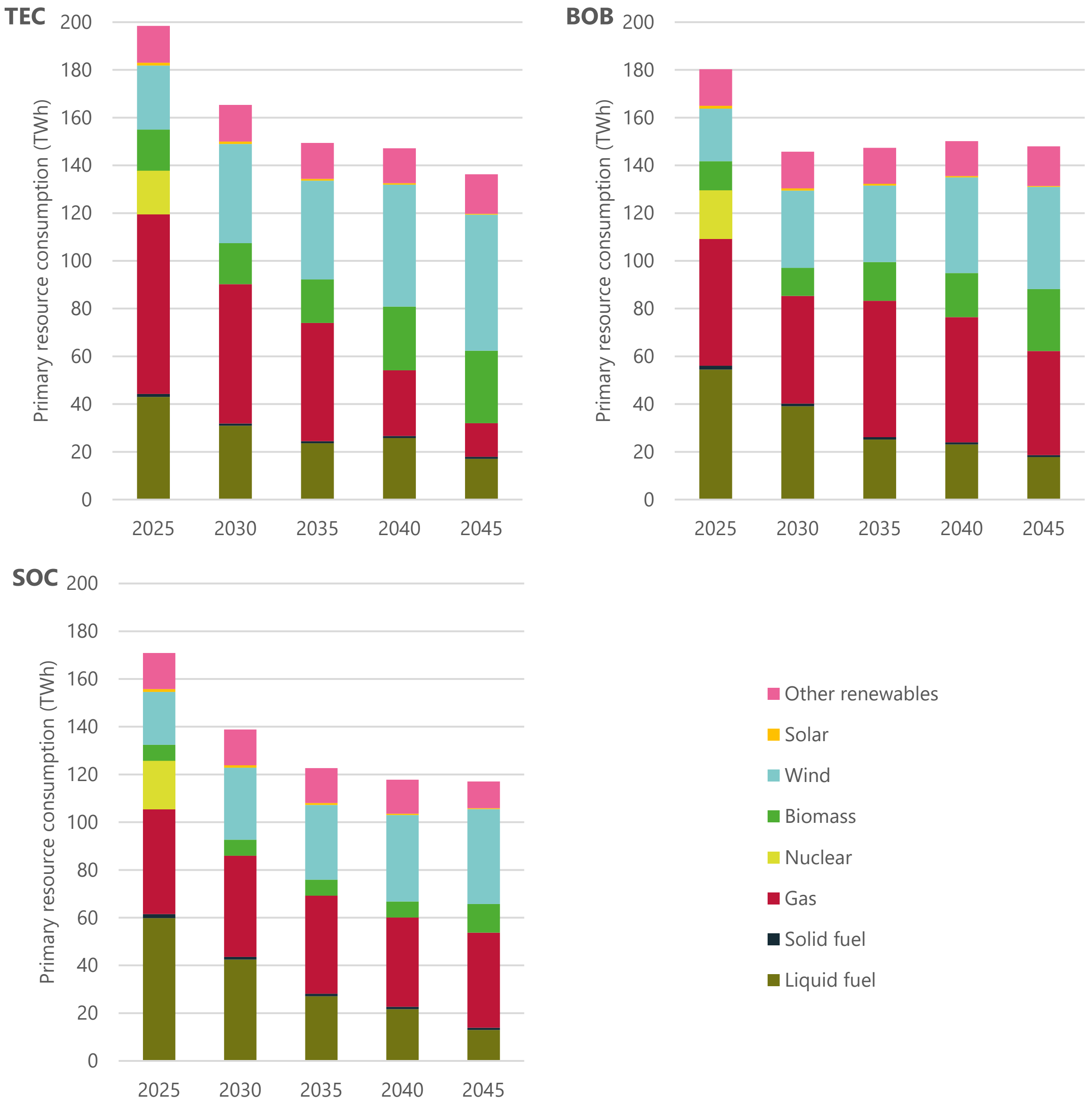

Figure 3.5: Primary resource consumption in Scotland for TEC, BOP and SOC. Other renewables include hydro, tidal and energy from waste; liquid fuel includes biofuel imports

The general trend for each of the scenarios is a move away from fossil and nuclear fuels as primary resource to renewable sources. The former is driven by model choices and the latter by the constraints placed on the model in relation to nuclear generation in Scotland. The shift away from fossil fuels is most obvious for liquid fossil fuels which are used in aviation, industry and road transport. Decarbonisation of road transport by electrification and industry by fuel switching to electricity and hydrogen explain the fall in liquid fuel consumption.

Aviation remains a difficult area to decarbonise. Within ESME the only available decarbonisation option for aviation is to replace old, inefficient aircraft with newer ones with better fuel efficiency (in reality potential options might include electric/hydrogen-fuelled aircraft and other low/zero emission fuels). In SOC, demand for air travel declines over the pathway allowing a greater reduction in liquid fuel consumption compared to TEC and BOP.

Natural gas use is more complex. In 2025, natural gas is used in power, residential heating and industry in all scenarios. In TEC and BOP, in 2030, natural gas is used in the production of blue hydrogen and in CCGTs with CCS. SOC imports most of its hydrogen from ROUK, which, especially during the 2030s, is predominantly produced from methane reformation. BOP sees a swell in gas consumption for hydrogen produced and consumed within Scotland. Gas consumption in TEC shows a continual decline in gas consumption throughout the pathway. This begins as a decline in gas for heating and in industry and continues as hydrogen production from electrolysis and BECCS increases.

3.2 Supplying zero carbon energy

Electricity and hydrogen become two essential zero carbon (at point of use) energy vectors supplied to Scottish homes and businesses. This section delves into these key vectors to understand the key differences in outcomes across three scenarios.

3.2.1 Electricity generation (production and capacity)

Electricity generated by unabated gas plant and nuclear fission reactors is assumed to cease by 2030 in all scenarios, in line with expectations and Scottish Government’s position on current nuclear technologies (as noted in Table 2.4). As a result, electricity generation in Scotland is overwhelmingly renewable and concentrated in onshore and offshore wind.

In TEC and BOP this is a result of minimum build constraints to reflect an estimated range of the capacity being delivered as part of ScotWind on top of that stated in the Scottish Government’s offshore wind policy statement. In SOC, it is a modelled outcome produced by the constraints on unabated gas plant and nuclear generation in combination with the legislated GHG targets.

Figure 3.6 shows the result of the minimum onshore and offshore wind build constraint on the scenarios with TEC and BOP. Both scenarios install a great deal more generation capacity than SOC the majority of which is on and offshore wind.

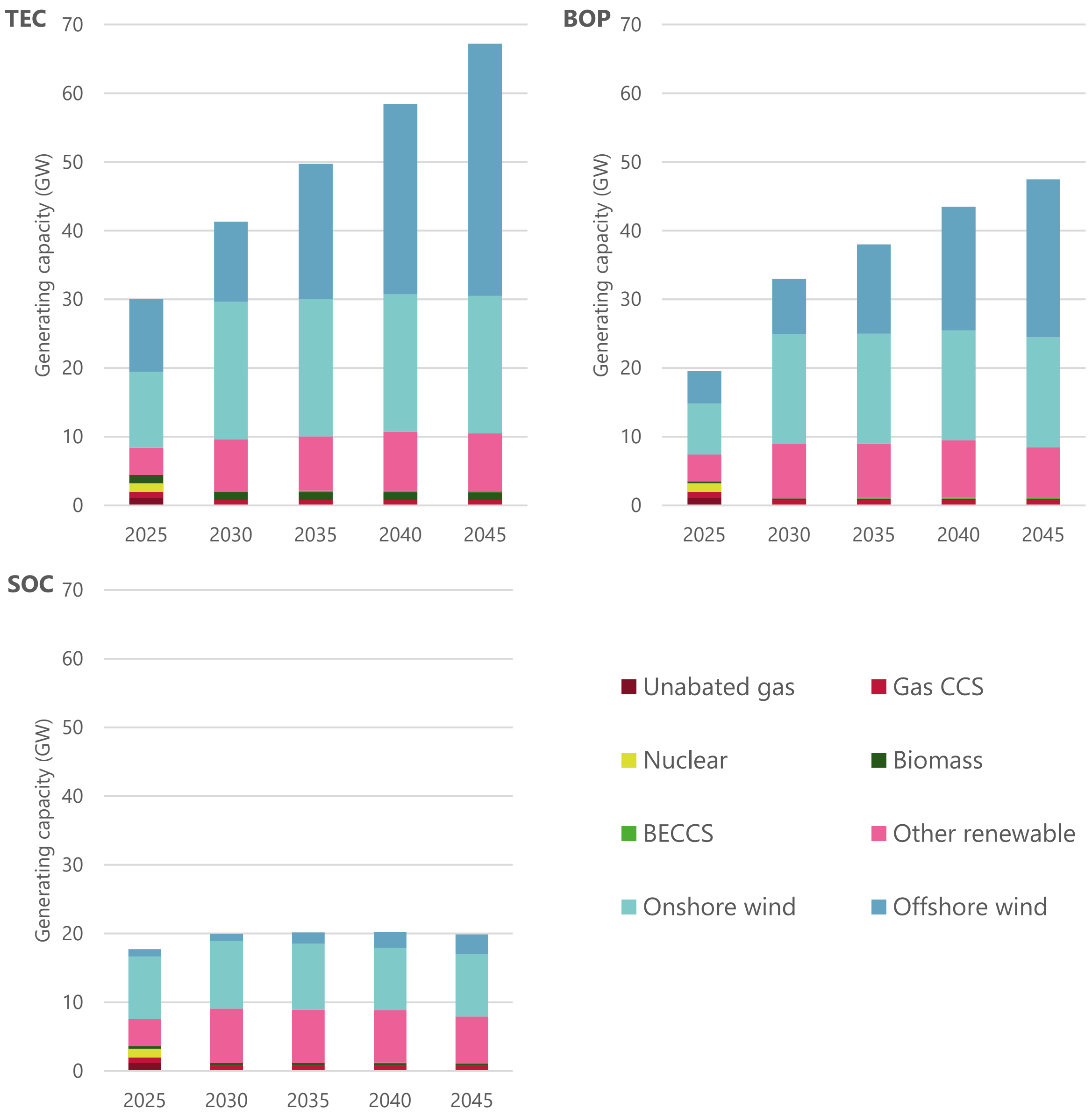

Figure 3.6: Electricity generating capacity in Scotland for TEC, BOP and SOC. Other renewables include energy from waste, tidal, hydroelectric, solar and hydrogen turbines

The total generating capacity seen in TEC and BOP is comparable to the amount seen in National Grid's Consumer Transformation and System Transformation scenarios respectively (National Grid, 2021). Consumer Transformation and System Transformation scenarios are presented in the Electricity Ten Year Statement (ETYS) and indicate a rapid increase in generating capacity over the next ten years, also seen in TEC and BOP. The majority of this capacity is expected to be wind.

The chart on the left in Figure 3.7, Figure 3.8 and Figure 3.9 shows the amount of electricity being produced by the Scottish power sector in TEC, BOP and SOC respectively. The black line indicates the electricity demand in Scotland. The chart on the right shows the amount of electricity produced and consumed within Scotland and exported from Scotland to ROUK.

The charts clearly show the effect of high wind capacity driven by implied Scottish Government policy in TEC and BOP, with Scotland being a significant net exporter of electricity as generation far outweighs demand. A similar outcome was seen in ETYS, with National Grid expecting Scotland to be an exporter of power to England most of the time

(National Grid, 2021). Without minimum build constraints applied to on and offshore wind, the SOC scenario is free to size Scottish generation subject to purely techno-economic considerations. The result of this is a generation sector sized more closely to match Scottish demand for electricity over the course of a year. From a techno-economic perspective, this avoids the cost of unnecessary generating capacity (unnecessary in terms of purely meeting Scottish electricity demand) and grid reinforcement needed to support high capacities of renewable generation. However, models such as ESME do not consider the economic advantages Scotland might enjoy by being a net exporter of electricity. With the majority of baseload generation (nuclear fission and unabated gas plants) exiting the Scottish power sector, all three scenarios are likely to require some imports from ROUK during times of low renewable output.

In line with current expectations, unabated gas capacity exits the power sector by 2030 in all scenarios and is replaced by combined cycle gas turbines (CCGT) with CCS from 2035 onwards. Initially CCGTs with CCS operate throughout the year supplying baseload[4] electricity. As time goes on, and GHG targets get stricter, the operation of these plants evolves: by the mid-2030s/40s they operate mainly in the winter months again supplying baseload electricity during this colder period but also during anytime renewable output is low. This would require a suitable market mechanism to support such seasonal use and ensure capacity is available when needed.

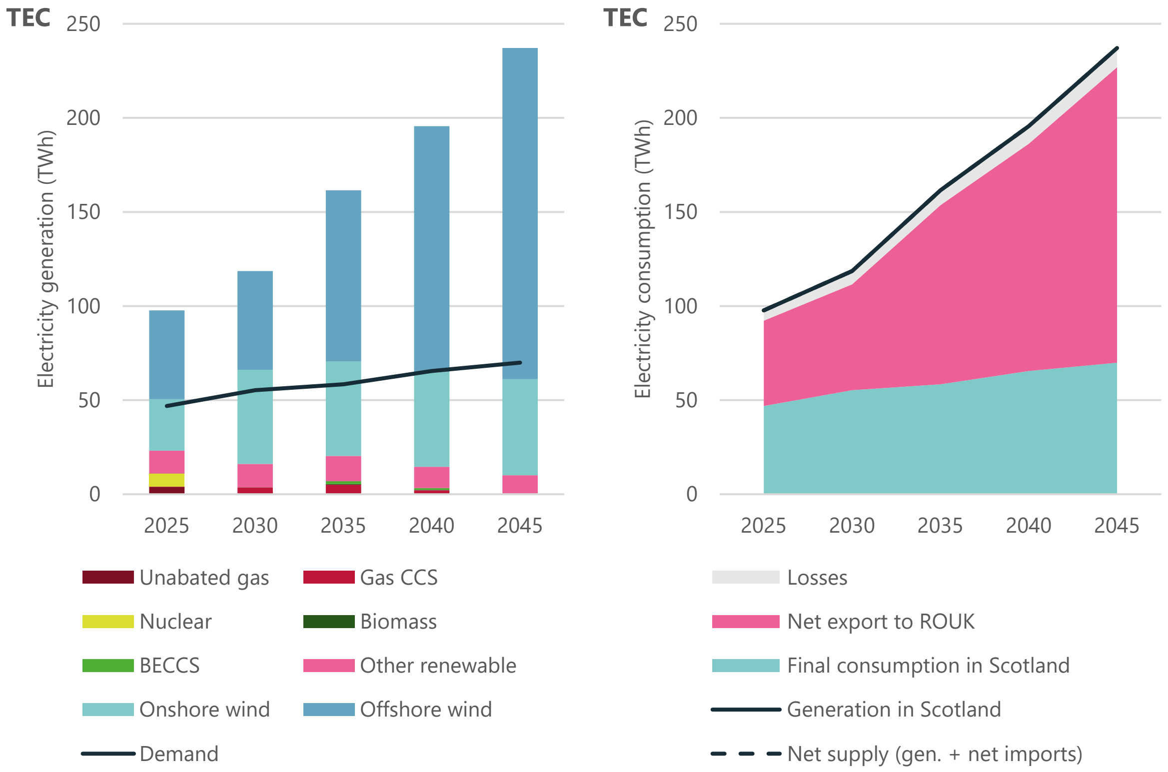

Figure 3.7: Left: Electricity generation in Scotland for TEC. Other renewables include energy from waste, tidal, hydroelectric, solar and hydrogen turbines. Right: Net import/export of electricity from/to ROUK for TEC

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[4] In this context, we define baseload as a constant, 24/7 supply of an energy carrier. The capacity of such supply is typically aligned to minimum energy demand of an energy end-use within a sector in a typical period

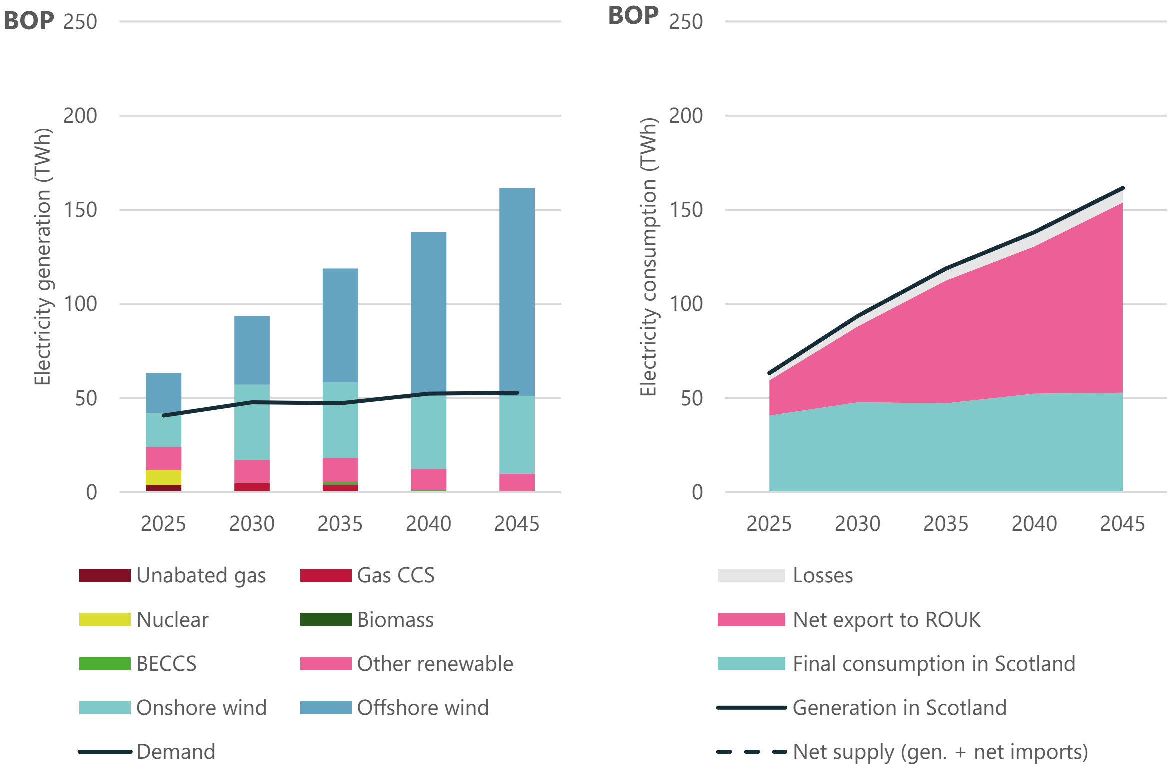


Figure 3.8: Left: Electricity generation in Scotland for BOP. Other renewables include energy from waste, tidal, hydroelectric, solar and hydrogen turbines. Right: Net import/export of electricity from/to ROUK for BOP

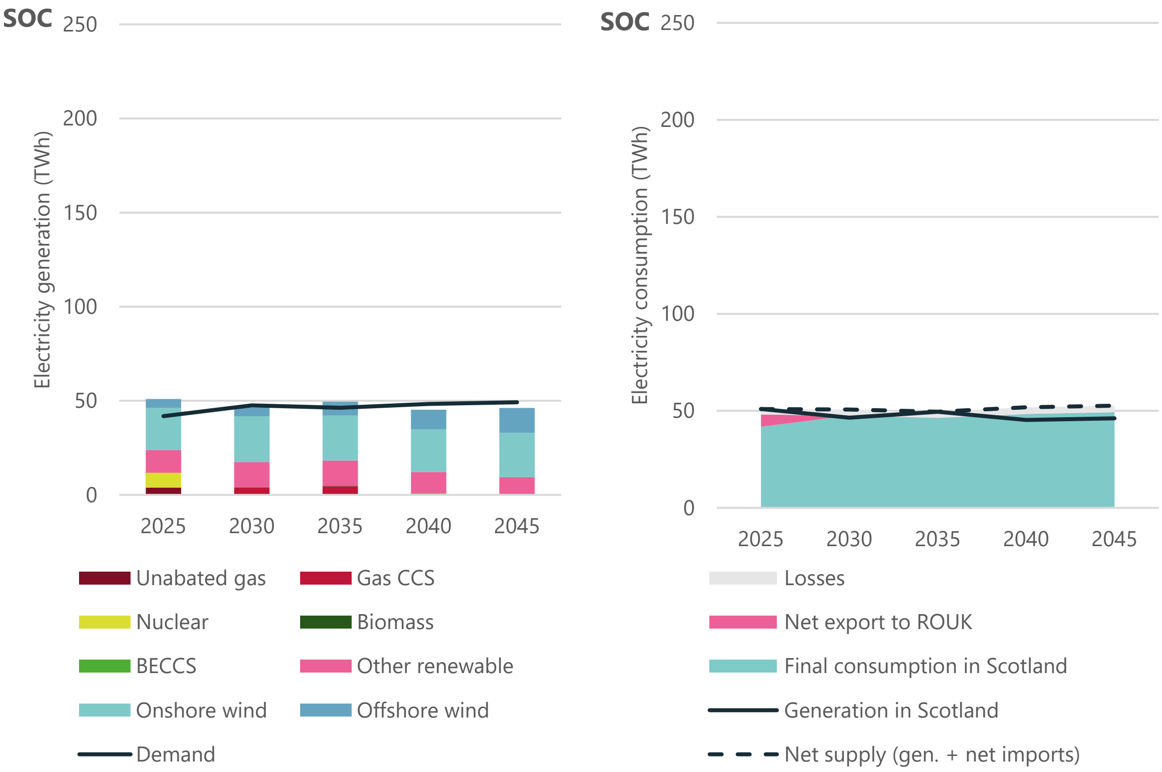


Figure 3.9: Left: Electricity generation in Scotland for SOC. Other renewables include energy from waste, tidal, hydroelectric, solar and hydrogen turbines. Right: Net import/export of electricity from/to ROUK for SOC

By 2045 emissions from CCGT with CCS plants are prohibitive given the net zero target and these plants operate purely during the coldest winter days providing back-up capacity to support a highly renewable power sector.

As well as gas plants, hydrogen turbines provide another form of dispatchable generation, this time being zero carbon. These are first deployed in 2030 and follow a similar evolution in operating profile as abated gas plants, moving from providing baseload to flexibility. The driver for this however is less to do with emissions and more to do with competing applications of hydrogen across the whole of the UK to which Scotland is a key supplier.

Producing more hydrogen is an option, and indeed hydrogen production does increase, but there are trade-offs to doing this related to cost of electrolysis, emissions from methane reformation and supply of biomass (refer to Figure 3.10 for more information).

3.2.2 Import and export of electricity

The generation charts above (Figure 3.7, Figure 3.8 and Figure 3.9) show Scotland to be a net exporter of electricity to ROUK in TEC and BOP and an overall a net importer in SOC. In 2025, almost half the electricity generated in Scotland in TEC is exported to ROUK. This increases to two thirds by 2045. BOP has more moderate amounts of on and offshore wind, which impacts the amount of exported electricity. This reduces the respective figures to 30% in 2025 and 60% of generation in 2045. Generation in SOC is more closely aligned to the demand although there is some export in 2025. Overall however, SOC imports around 6TWh from 2040.

It would be possible for some of the exported electricity in TEC and BOP to be converted to green hydrogen, but the model chooses not to. The possible reasons for supplying the ROUK with electricity instead of converting to green hydrogen include:

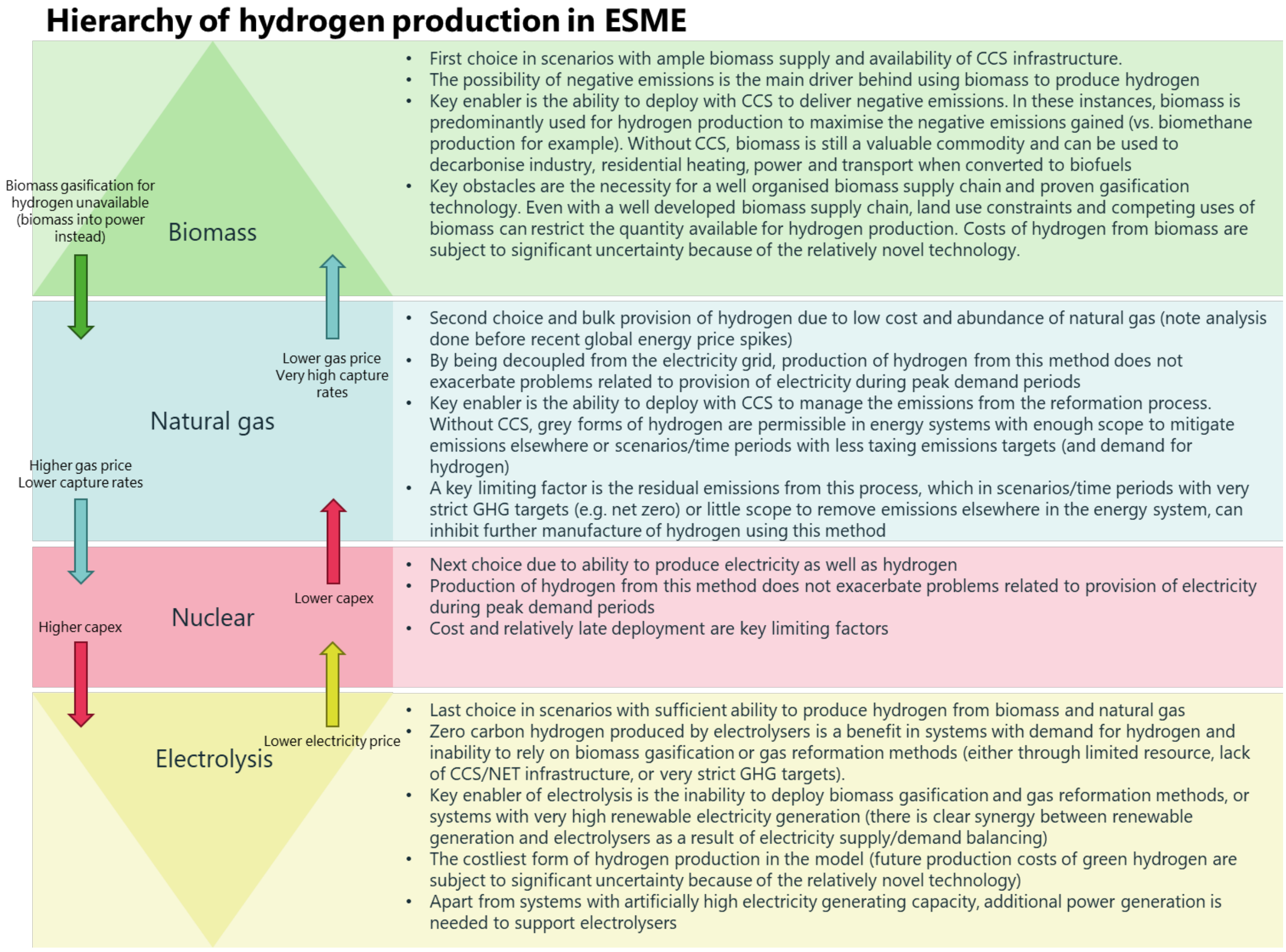
- *ROUK demand:* There is demand for electricity in ROUK as key sectors of the energy system decarbonise. If the exported Scottish electricity was instead converted to hydrogen, then the ROUK would have to build additional generating capacity to meet its own demands. This would increase the total system cost for the UK energy system in the model, something it is trying to minimise.
- *Hydrogen generation options:* Hydrogen can be generated in several other ways (e.g. biomass gasification and methane reformation both with CCS) that are compatible with GHG targets. ESME modelling does not over-deliver on national GHG targets by producing green hydrogen because this would be more costly. Electrolysers have a relatively high capital cost in ESME compared to other production methods.

3.2.3 Hydrogen production

There are three broad categories of hydrogen production modelled in ESME:

- Reformation of natural gas both with CCS (also called blue hydrogen) and without (referred to as grey).
- Electrolytic hydrogen (also referred to as green hydrogen, especially when powered solely by renewable electricity, but sometimes referred to as yellow when powered by grid electricity, which may or may not still rely on fossil fuel powered generation).
- Gasification of biomass both with and without CCS.

Given ESME's overarching challenge to deliver an energy system that satisfies demands whilst meeting GHG targets for the lowest system cost (tangible costs associated with capital expenditure and operation/maintenance), a hierarchy of hydrogen production methods becomes apparent, which can sometimes seem counterintuitive. The diagram below presents this hierarchy and explains the drivers/constraints associated with each technology option, with some indications to how this might change under a different set of assumptions.



- First choice in scenarios with ample biomass supply and availability of CCS infrastructure.
- The possibility of negative emissions is the main driver behind using biomass to produce hydrogen
- Key enabler is the ability to deploy with CCS to deliver negative emissions. In these instances, biomass is predominantly used for hydrogen production to maximise the negative emissions gained (vs. biomethane production for example). Without CCS, biomass is still a valuable commodity and can be used to decarbonise industry, residential heating, power and transport when converted to biofuels
- Key obstacles are the necessity for a well organised biomass supply chain and proven gasification technology. Even with a well developed biomass supply chain, land use constraints and competing uses of biomass can restrict the quantity available for hydrogen production. Costs of hydrogen from biomass are subject to significant uncertainty because of the relatively novel technology.

- Second choice and bulk provision of hydrogen due to low cost and abundance of natural gas (note analysis done before recent global energy price spikes)
- By being decoupled from the electricity grid, production of hydrogen from this method does not exacerbate problems related to provision of electricity during peak demand periods
- Key enabler is the ability to deploy with CCS to manage the emissions from the reformation process. Without CCS, grey forms of hydrogen are permissible in energy systems with enough scope to mitigate emissions elsewhere or scenarios/time periods with less taxing emissions targets (and demand for hydrogen)
- A key limiting factor is the residual emissions from this process, which in scenarios/time periods with very strict GHG targets (e.g. net zero) or little scope to remove emissions elsewhere in the energy system, can inhibit further manufacture of hydrogen using this method

- Next choice due to ability to produce electricity as well as hydrogen
- Production of hydrogen from this method does not exacerbate problems related to provision of electricity during peak demand periods
- Cost and relatively late deployment are key limiting factors

- Last choice in scenarios with sufficient ability to produce hydrogen from biomass and natural gas
- Zero carbon hydrogen produced by electrolysers is a benefit in systems with demand for hydrogen and inability to rely on biomass gasification or gas reformation methods (either through limited resource, lack of CCS/NET infrastructure, or very strict GHG targets).
- Key enabler of electrolysis is the inability to deploy biomass gasification and gas reformation methods, or systems with very high renewable electricity generation (there is clear synergy between renewable generation and electrolysers as a result of electricity supply/demand balancing)
- The costliest form of hydrogen production in the model (future production costs of green hydrogen are subject to significant uncertainty because of the relatively novel technology)
- Apart from systems with artificially high electricity generating capacity, additional power generation is needed to support electrolysers

Figure 3.10: Hierarchy of hydrogen production methods in ESME. Note that in ESME, imports of natural gas are unlimited whilst in reality there are a number of factors that can limit the availability of this resource. Secondly, the gas price in ESME is based on BEIS fossil fuel price projections and are reflective of long-term trends and do not account for short-term volatility in gas price as experienced in reality. Blue hydrogen production in ESME is sensitive to gas price and scenarios with higher gas prices are likely to see a decrease in the amount of blue hydrogen production in favour of electrolysis. Production of hydrogen using advanced nuclear reactors has been excluded from the options for Scotland in line with expectations that nuclear fission will not feature in Scotland's energy mix.

There are some factors that techno-economic models like ESME do not explicitly include which can lead to decisions that might differ from those of real-world stakeholders. Some important considerations include:

- The temporal resolution in ESME is relatively coarse, dividing days into five time-slices. System balancing on a sub-hourly basis, as well as provision of other flexibility services might well be factored into the business case for certain technologies but are not well-represented in ESME.
- Additional real-world requirements that can be met by some technologies may not be factored into models like ESME. For example, the purity of hydrogen produced by electrolysers might be an important consideration for certain hydrogen applications.

- ESME is focused on satisfying energy demand in the UK and does not consider the potential for exporting energy vectors to other parts of the world.

The TEC scenario has incorporated, in the form of a model constraint, the aspiration for 5GW of hydrogen production in Scotland by 2030. This has been constrained in ESME to be 3GW of electrolysers and 2GW of blue hydrogen production. Without this constraint it is unlikely that the model would choose to install this amount of hydrogen production capacity in Scotland as early as 2030. Indeed, the BOP scenario (which is not subject to this constraint) only installs 1GW of hydrogen production in Scotland in 2030, all of which is blue. Nevertheless, post-2030, hydrogen production in Scotland ramps up driven by an increase in the demand for hydrogen to support decarbonisation of residential heat and industry (Figure 3.11).

Figure 3.11: Hydrogen production in Scotland for TEC, BOP and SOC

The TEC scenario has the most developed biomass supply chain in Scotland of all the scenarios and by 2040, biomass gasification combined with CCS to produce hydrogen is the largest consumer of biomass in Scotland. This both contributes to the demand for hydrogen and delivers negative emissions which are of great value to the TEC scenario where energy demands are high across all sectors of the energy system and associated

GHG emissions need to be mitigated. The 3GW of electrolysers installed in 2030, increase their output by 2045 from 3-4TWh to 9TWh taking advantage of the high offshore wind capacity.

Interestingly, the quantity of offshore renewables does not prompt additional electrolyser capacity to be installed in the modelling. Instead, there is value in exporting this electricity to ROUK, which is also faced with the challenge to decarbonise its energy system. Electricity is a major energy vector in the decarbonisation of homes, industry and transport and so the ability to use this directly, rather than convert to hydrogen (and in some instances back to electricity) is of greater value to the model.

The method of bulk hydrogen production is the same in TEC and BOP scenarios, that is, reformation of methane, with biomass playing a major role in hydrogen supply by 2040. Electrolysis does not feature in BOP, nor would it have done in TEC if there was no minimum build constraint. The reasons for this are related to the characteristics of electrolysers as modelled in ESME (explained in Figure 3.10) but may also be a result of certain characteristics of the model itself (drawn out above). In reality, green hydrogen production projects are already going ahead in Scotland (SSE, 2022), and recent supply and price issues with natural gas could lead to a very different hierarchy of production methods.

The SOC scenario produces the least amount of hydrogen in Scotland meaning Scotland is a net importer of hydrogen from ROUK. There are a number of important reasons for this:

- Low overall energy demand means hydrogen consumption is less
- Less biomass available: this has two knock-on effects:
    i. The quantity of hydrogen that can be produced from biomass is more limited due to competition across the energy system for a smaller supply of biomass.
    ii. Negative emissions generated by BECCS processes (either in power or hydrogen production) are smaller meaning residual emissions from blue hydrogen production are prohibitive.
- Electricity supply in Scotland is enough to meet Scottish demand. There is no "excess" to be utilised by electrolysers.
- The SOC scenario assumes a slower commercialisation of CCS, which delays roll-out of BECCS and blue hydrogen production

In all three scenarios Scotland is an importer of hydrogen until 2035 (Figure 3.12) mainly to support decarbonisation of industry from the mid-2020s. During this time, small scale CCS demonstrators and strict emissions targets mean Scotland's H_2 production capability is insufficient to support demand. Scotland is therefore the major consumer of hydrogen produced in the ROUK.

In the TEC scenario, Scotland is a net importer of hydrogen from the ROUK until around 2040. By the 2040s, it is able to just about satisfy domestic demand for hydrogen. Despite emissions removal technologies like DACCS, commercial rollout of CCS and high quantities of biomass, TEC is unable to become a net exporter of hydrogen in the way BOP is. The reason for this is related to the slower shift away from gas boilers and adoption of zero carbon cars. This generates emissions that prohibit the bulk production of hydrogen from methane reformation which impacts overall production quantities in this scenario. By the mid-2030s, production of hydrogen in BOP ramps up thanks to commercial scale CCS roll-out enabling blue and BECCS hydrogen. Supply outweighs demand and Scotland exports to ROUK. SOC remains an importer of hydrogen throughout the pathway because of reasons outlined above.

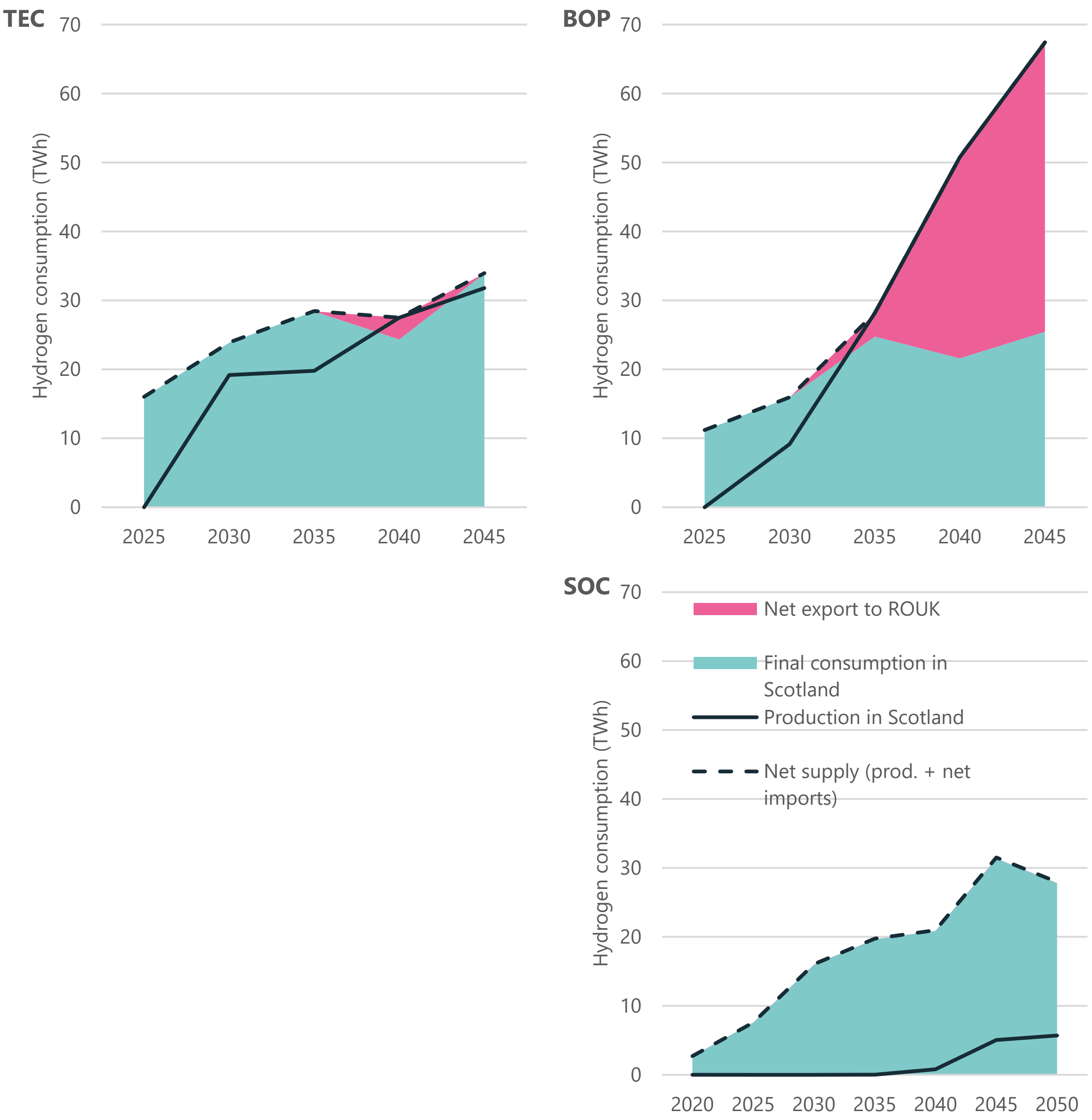


Figure 3.12: Net import/export of hydrogen from/to ROUK for TEC, BOP and SOC

3.3 Greenhouse gas removal

3.3.1 Engineered removals and captured CO_2

Technological innovation in TEC and BOP mean CO_2 capture from energy conversion processes and directly from the air are a key feature of the scenarios from 2030 onwards. CCS develops in the power, blue hydrogen production and industry sectors and then used in combination with biomass in 2035. SOC does not install any engineered removal technology such as direct air capture. In this scenario, early CCS is of a smaller scale in 2030 but still starts in power and industry. It is not until 2040 that CCS and biomass are combined mainly to produce hydrogen and negative emissions to combat residual emission in land use and industry. Figure 3.13 shows the amount of CO_2 captured in Scotland in TEC, BOP and SOC.

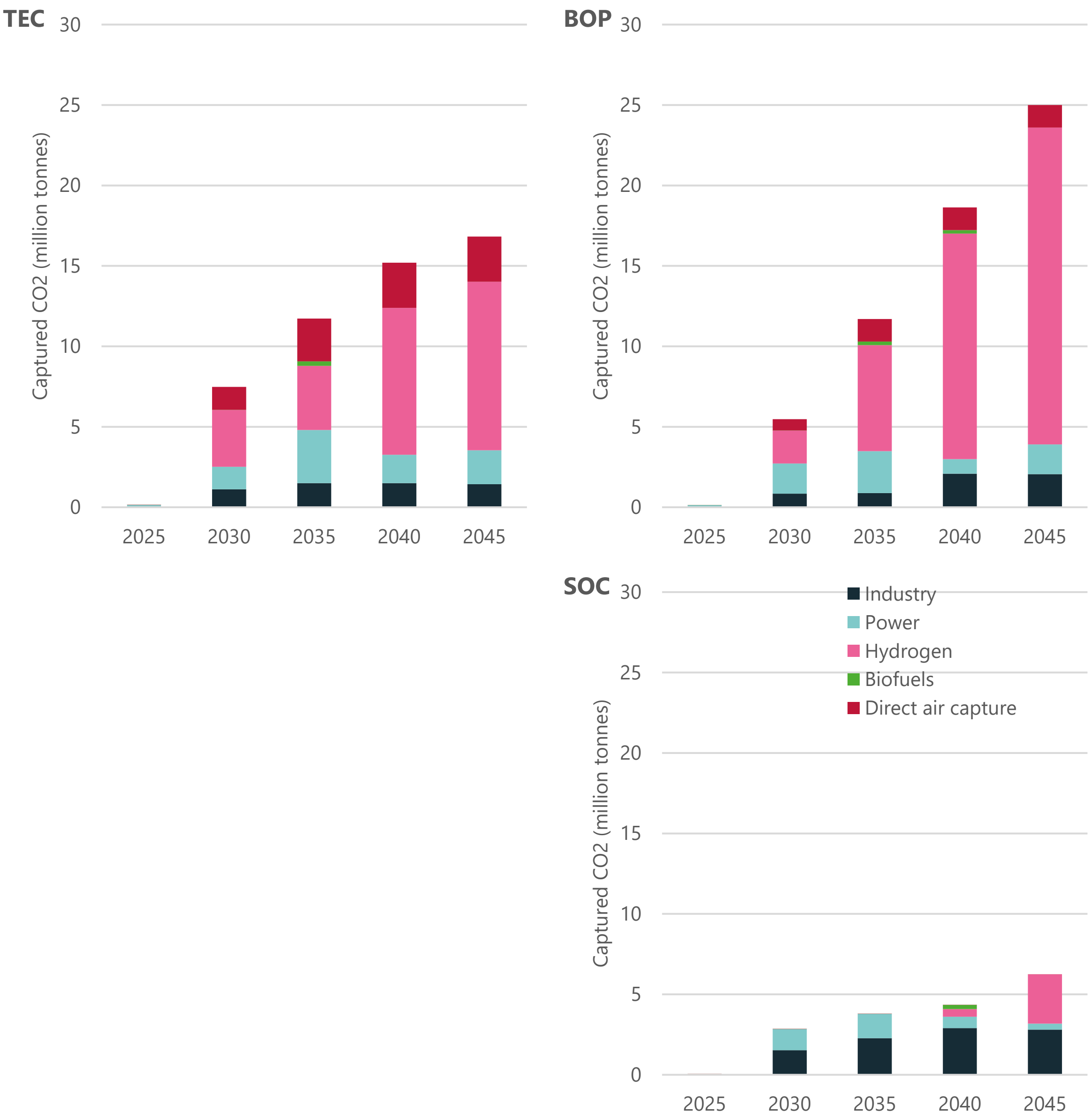


Figure 3.13: Capture CO_2 in Scotland for TEC, BOP and SOC

Of all the scenarios, TEC captures the most CO_2 in the 2030s. By 2040, BOP and TEC are capturing similar amounts but by 2045, BOP is capturing the most CO_2. This is because BOP produces more hydrogen from natural gas than TEC (which has more biomass and electrolyser capacity). Hydrogen production (both BECCS and from natural gas) are the biggest sources of captured CO_2. The delay in hydrogen production with CCS in SOC really limits the amount of CO_2 that is captured. Limited biomass supply also impacts the amount of BECCS hydrogen plants that can be deployed. This in turn reduces the amount of negative emissions that can be achieved meaning blue hydrogen is non-viable from an emissions standpoint.

3.3.2 Nature-based removals and CO_2 savings

ESME is first and foremost an energy systems model, which means it is only concerned with designing systems using technologies that satisfy energy demands in the main sectors. However, since net zero incorporates not just CO_2 but other GHGs (e.g. CH_4, N_2O and F-gases) and non-energy sectors such as land use, these need to be accounted for in the modelling. ESME does this by calculating emissions trajectories for each of the non-energy sectors in the UK's economy. It factors in known non-energy related GHG emissions into the design of the energy system to ensure non-energy and energy sector emissions sum to zero.

Nature-based removal of GHG and land use emissions, including those linked to diet and agriculture, are examples of “off-model” decisions to be factored into the scenarios; assumptions related to these emission sources are presented in the Scenarios Tables. TEC, BOP and SOC assume different amounts of sequestration from tree-planting and peatland restoration as well as savings achieved from changes in diet away from red meat and dairy. Figure 3.14 shows the GHG emissions savings achieved in Scotland for each of the scenarios due to nature-based removals and changes in diet.

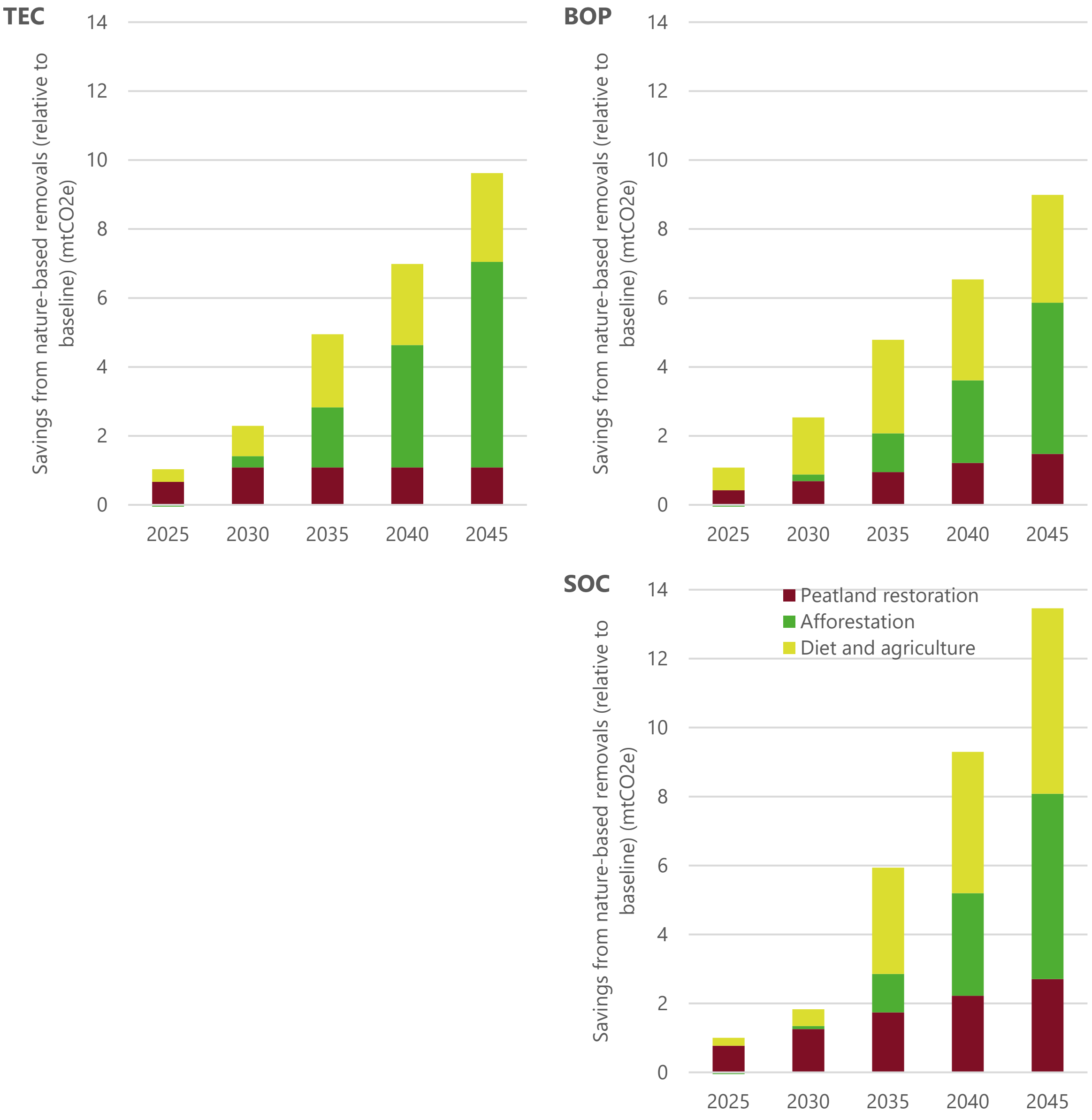


Figure 3.14: GHG savings from nature-based removals and diet change in Scotland for TEC, BOP and SOC

Emissions trajectories for peatland restoration were informed by (CEH, 2017); forestry emissions and savings from diet change (and agricultural practices) from (CCC, 2020). Scenario narratives from (CEH, 2017) and (CCC, 2020) were aligned with the general philosophy of the scenarios presented here; for example, SOC aligns well with CCC’s ‘Widespread Engagement’ scenario whilst TEC and BOP are most closely related to ‘Widespread Innovation’ and ‘Balanced Pathway’ respectively.

Widespread Innovation, delivers greater tree-planting rates and sequestration than Widespread Engagement which is why emissions savings from afforestation are higher in TEC than SOC. However, peatland restoration rates are higher in SOC than the other scenarios. So too is people's willingness to shift their diets to ones with a lower carbon footprint; therefore, GHG savings related to diet and agriculture are highest in SOC.

3.4 Bioenergy

Bioenergy is another important energy vector for decarbonisation of the Scottish economy. It can be used to produce electricity and hydrogen or used directly to deliver energy end uses like residential heat.

3.4.1 Biomass production

The three scenarios are characterised by different levels of biomass resource available. TEC is a relatively high biomass scenario with peak supply in Scotland of around 25TWh by 2045, supplemented by a further 5.2TWh of imports. The BOP scenario has slightly less domestic biomass with supply peaking at 21TWh in 2045. SOC is a low biomass scenario, with domestic supply remaining at current levels (approx. 7TWh/yr.) from 2020 to 2040 and increasing to 12TWh/yr. in 2045. There is no reliance on imported biomass in this scenario. In all scenarios, the assumption made in ESME is that biomass cannot be transported around the UK and must be consumed in the region it is grown.

3.4.2 Biomass consumption

When coupled with CCS, biomass can deliver negative emissions. This is known as BECCS (bioenergy with carbon capture and storage) and can be used in electricity generation, hydrogen production, or in industrial processes.

Whilst there is some BECCS power in TEC, BOP and SOC, from 2035 to support a renewable-heavy power sector, the amount is relatively low. The power sector has a number of technology options that allow it to decarbonise entirely without the use of biomass. Even though BECCS in power would create negative emissions, there is sufficient electricity being produced from renewables. Therefore, BECCS is of more value to decarbonise processes that are more limited in their technology options, for example industry and hydrogen production. Biomass consumption in industry is assumed to be relatively low in Scotland in the three scenarios, so there is only residual baseline amount being used from 2020. So, this leaves hydrogen production, which once CCS has reached commercial scales, becomes the dominant use of biomass in Scotland and the ROUK.

Before CCS is deployable at scale, biomass is used differently. It is used as carbon neutral energy vector in residential and industrial heating, biofuel/biomethane production and power generation (see emissions from biomass section below). In TEC especially, with a slower shift away from gas boilers and ICE/hybrid cars, biomass plays an important role in decarbonising these sectors in the form of biomethane and biofuel. In TEC, SOC and BOP, industrial consumption of biomass is constrained to baseline levels in Scotland with no option to increase consumption in this sector. Power is largely decarbonised by 2030 in all scenarios with relatively moderate amounts of biomass fired generation. This leaves residential heating as a key end use for biomass in Scotland.

There is a period spanning from the mid-2020s to the mid-2030s, when CO_2 targets, particularly in Scotland, are getting tighter but key technologies like CCS have not yet reached large scale deployment - the power sector necessarily does a lot of the heavy lifting during this time. For other sectors, these years are quite challenging because they either rely on key technologies like CCS/energy efficiency measures (e.g. in industry), or societal shifts in behaviour to reduce energy consumption or adopt novel technologies (e.g. in heating and transport). Biomass plays an important role meeting end use demands in a relatively familiar and understandable way e.g. in biomass boilers. We also see biomass being used to produce biofuels in an effort to decarbonise transport, particularly heavy-duty vehicles, with novel zero carbon powertrains in their infancy. Biomethane reduces net emissions from gas boilers in TEC in which reliance on gas boilers continues in the 2020s/30s.

3.4.3 Emissions from biomass

In most accounting of bioenergy emissions, the use of biomass is assumed to be net zero i.e., combustion of biomass releases the same amount of CO2 that was absorbed during its growth. In ESME, some allowance is made for emissions related to harvesting and transport of biomass and so its use is very slightly net positive (unless combined with CCS) - this leads the model to prefer domestically grown biomass over imported.

3.5 The role of natural gas

There is a role for natural gas in the Net Zero transition in the scenarios presented but this role evolves over time from the predominant supplier of heat in homes and industry, to the primary feedstock for hydrogen production. As an international market, the source of natural gas, and for that matter oil, is not modelled explicitly in ESME – ESME provides an overall level of Scotland and ROUK demand for these products.

It is therefore not possible to provide specific insights around the future of the UK Continental Shelf (UKCS), other than to say that there will be a residual envelope of demand as we transition to Net Zero. The level of that demand met by the UKCS O&G sector will be subject to a range of market, economic, political and geopolitical considerations.

Recent events in Europe highlight the important role broader geopolitical and security of supply considerations will play in the future of the UKCS. These considerations and their interactions are more likely to shape the scenarios and outcomes for that sector, within the domestic demand envelopes that the three scenarios explored in this exercise imply.

Some of these considerations will also apply to choices between green and blue hydrogen production. Being able to decouple the provision of energy to the UK from wider global issues by being largely self-sufficient in electricity and hydrogen production could offer strategic security benefits. Green hydrogen production is certainly able to deliver this, assuming Scotland or the UK has access to the underlying technology.

3.6 Meeting energy end use demand

3.6.1 Electricity consumption

Electrification is a key route to decarbonising end uses of energy including heat, transport and industry. There are also potential new uses of electricity that are currently not seen in today's energy system including for large scale hydrogen production and direct air capture of CO_2. Figure 3.15 shows how the consumption of electricity in Scotland increases from the mid-2020s until 2045 and where that electricity is being used in the TEC, BOP and SOC scenarios.

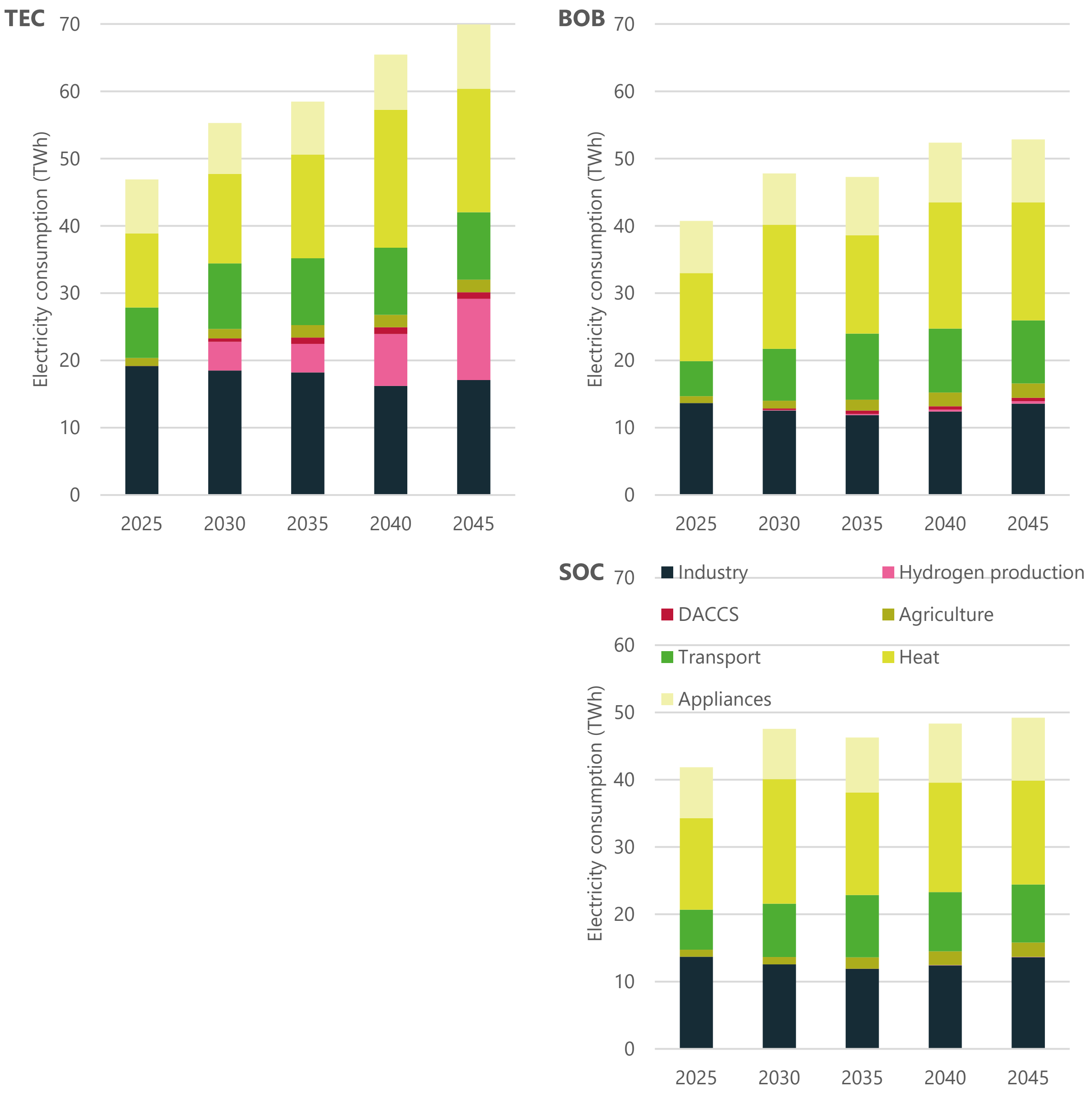


Figure 3.15: Electricity consumption in Scotland in TEC, BOP and SOC. DACCS = Direct air carbon capture and storage

The most noticeable increase in electricity consumption in all three scenarios is in the transport sector. This is a direct result of the ban on new sales of internal combustion engine (ICE) cars and vans in 2030 and 2035 respectively, which results in a switch to electric cars and vans. There is also a similar constraint applied to new buses from 2025 and new HGVs from 2035 in TEC and 2040 in SOC and BOP. New buses are battery electric, whilst HGVs are either dedicated battery electric vehicles or electric/hydrogen hybrids. Agricultural practices and vehicles as well as other heavy-duty vehicles such as excavators increasingly use electricity in these scenarios.

Overall electricity demand is highest in TEC because it is a high energy demand scenario. In addition to meeting typical electricity demand, TEC also sees new demands from electrolysers and direct air capture plants from 2030.

Electricity consumption for residential heating and appliances is relatively uniform throughout each pathway. This is a result of increasing demand (from new homes and replacement of old fossil-based heating systems) being offset by efficiency improvements to household appliances, switching to more efficient LED lighting and improved coeffect of performance of heat pumps. Average building thermal efficiency also increases due to stricter standards for new homes but also retrofitting of building fabric improvements to the existing housing stock – this reduces the heating loads and therefore electricity consumption by electric-based heating.

Industrial electricity consumption appears to decrease slightly over time. This is largely because of assumed efficiency improvements reducing overall energy consumption.

3.6.2 Hydrogen consumption

Hydrogen provides the energy system with a zero-carbon, flexible energy vector that can be used to deliver a range of end uses in transport, heating and industry. It also offers a form of dispatchable power generation to overcome intermittency challneges associated with renewable generation. Figure 3.16 shows where in the Scottish energy system hydrogen is being used and in what quantities.

The overall amount of hydrogen being consumed is largely driven by the underlying assumptions around energy demand, with TEC consuming the most and SOC the least for most of the pathway. In all scenarios presented, industry is the dominant consumer of hydrogen. Small amounts of hydrogen are used to provide low carbon residential heat in the mid-2020s/30s. This increases throughout the pathway to become an important end use for hydrogen.

In 2030, hydrogen is used to provide dispatchable power. By 2040, the amount of hydrogen being used in hydrogen turbines decreases. The reason for this is related to how the hydrogen turbines are being operated. In their first decade of deployment, hydrogen turbines are operated to support the power sector in delivering some baseload energy. GHG targets tighten very quickly from 2020 to 2030, which drives a need for low and zero carbon electricity generation. Nuclear power and the unabated gas plant at Peterhead have also ceased operation and other sectors are increasing the consumption of electricity in an effort to decarbonise. In the second decade of operation, the role of hydrogen turbines evolves from baseload power generation to supporting peak provision of electricity.

Hydrogen turbine capacity is maintained to meet peak demands of electricity and support intermittent renewable generation (the peak period is a 1 in 20-year winter and also includes a period of low wind). A shift away from baseload generation helps to reduce the amount of hydrogen needed in the energy system along with the associated cost of generation. In theory, more hydrogen could be produced but there are challenges associated with this including finite biomass supply and residual emissions from blue hydrogen production.

Electrolysers could be used to convert some of the excess renewable electricity into hydrogen as a form of long term, seasonal storage of electricity. However, there are efficiency losses associated with converting electricity into hydrogen and back again, and as stated before there is a large demand for electricity across the entire UK, of which Scotland is a key supplier. Instead, hydrogen from blue and BECCS processes are used in smaller quantities to fulfill peak demands. Other storage options, working on different time scales, are used to balance supply and demand including pumped storage of electricity.

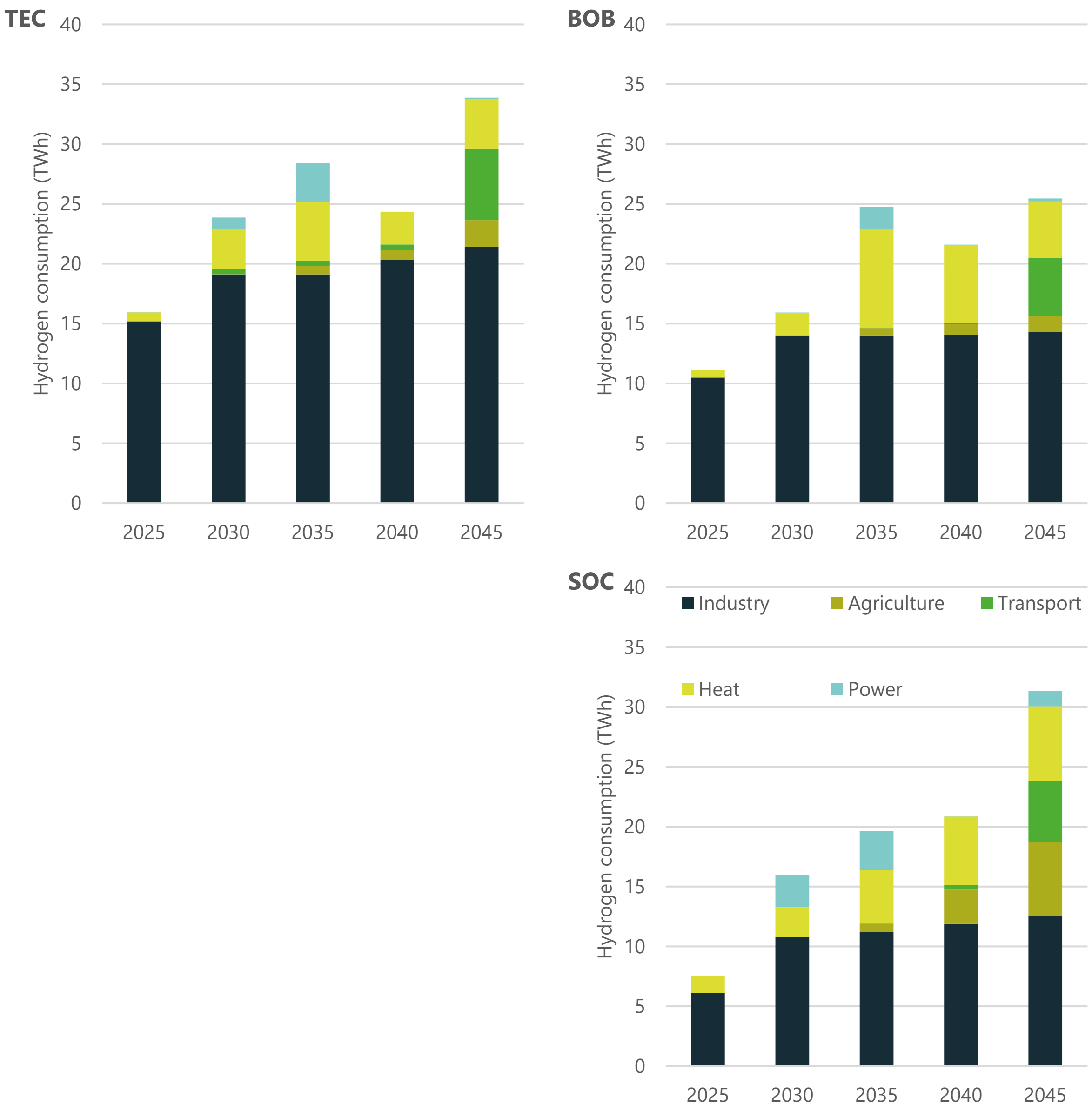


Figure 3.16: Hydrogen consumption in Scotland in TEC, BOP and SOC

3.6.3 Buildings and Heat

In today's energy system, natural gas is a fundamental supplier of heating in homes with around 80% of homes in the UK connected to the gas network. As Scotland transitions to net zero, the role for fossil fuels in supplying residential and non-domestic heat will need to be replaced with other energy vectors. Figure 3.17 shows how the Scottish residential and non-domestic heating sectors shifts from natural gas to three key zero carbon energy vectors: district heat, electricity and hydrogen.

Figure 3.17: Amount of heat (TWh) supplied to residential and non-domestic buildings in Scotland for TEC, BOP and SOC

In TEC, model constraints slow down the switch away from natural gas boilers. In response to this, the model uses biomass to produce biomethane which decarbonises the gas being supplied to homes and businesses. By 2045, homes and non-domestic buildings have entirely switched away from natural gas to electric-based heating, hydrogen and district heat. In SOC, the model is free to switch away from gas boilers sooner (i.e. there are no constraints on the speed at which gas can be eliminated from the heating sector). This happens by 2030, driven primarily by the tightening of emissions targets in Scotland[5]. To avoid a situation in which gas boilers reappear in the heating sector post-2030, a ban on new gas boiler sales was introduced to the model. Energy systems models such as ESME do not necessarily account for the practicalities of technology switching (i.e. the desire to minimise disruption to end users) and are able to "play the system" somewhat. For example, 2030 is a difficult year for the model given the

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[5] Note that whilst the same emissions targets apply in TEC, the gas boiler switch was artificially slowed down to reflect a scenario in which people are unable to switch away from gas. This allows us to observe what decisions the model makes in response to this to ensure emissions targets are met.

strict emissions targets in Scotland and many key low carbon/GHG removal options still in their infancy. During this year, the model can opt to reduce the output of high carbon technologies such as gas boilers provided there is sufficient heat being provided by alternative technologies. Post-2030, new technologies which can achieve significant decarbonisation in other aspects of the energy system reach commercial scale. In response, ESME can sometimes reintroduce higher carbon options elsewhere in the system (e.g. gas boilers) if it produces a lower overall system cost (the alternative might involve higher quantities or electricity and hydrogen to be produced and supplied to homes with the associated infrastructure costs including transmission and distribution).

The SOC heating system becomes net zero by 2030 but because people have adopted low energy lifestyles, the overall amount of heat supplied is less than in TEC. This is most noticeable in the number of homes connected to district heat networks or using biomass or hydrogen. BOP, with more technology options deployable than SOC (particularly GHG removals) and lower energy demand than TEC, is able to continue using small amounts of natural gas for heating up to 2040. Note that these two scenarios (BOP and SOC) display an unexpected result related to gas/hydrogen utilisation: Gas supplies less heat to homes and businesses in 2030 driven by the 2030 GHG target. However, hydrogen does not get deployed at scale until 2035. This would therefore represent a 5-year period during which the gas network is not being utilised. This is a modelling artefact and in reality, is a situation to be avoided, but it does highlight the challenge of heat decarbonisation.

Heat pumps are the mainstay of heat provision in Scotland being deployable in on and off-gas grid homes alike. Hydrogen for heat sees a surge in 2035 in TEC and BOP as Scottish hydrogen production ramps up due to CCS commercialisation. SOC sees a steadier increase in hydrogen for heat, relying mainly on hydrogen imported from other parts of the UK to meet demand. Akin to hydrogen turbines (explained above), there appears to be an evolving role for hydrogen boilers from supplying heat throughout the year to peak provision during the coldest winter periods as part of a hybrid heat pump system.

There are distinct advantages to operating hydrogen boilers as part of a hybrid heat pump system in a techno-economic model like ESME:

- Heat pumps can be sized to more closely meet baseload heat demands. This means smaller capacity heat pumps running more uniformly throughout the year. Smaller heat pumps are cheaper which helps to minimise the system cost.
- Meeting peak heat demands with electricity increases the amount of generating capacity needed along with the necessary grid reinforcement. Given that the peak period in ESME assumes heavily reduced output from wind turbines in conjunction with very cold temperatures, the Scottish power sector would need to rely on high capacities of dispatchable plant and storage to meet heating loads. This cost can be avoided by using hydrogen produced and stored throughout the year. Thermal storage in buildings also contributes to peak heat demand in hybrid and non-hybrid systems.
- Hydrogen boilers do not need to run throughout the year supplying baseload heat, which reduces the demand for hydrogen and therefore the amount that needs to be produced. This minimises the system cost because additional production capacity is avoided.

Of course, there are real world practicalities to bear in mind when considering hybrid hydrogen heat pump systems. Homes and businesses will need connection to a hydrogen network. This might be an existing gas network that has switched over to hydrogen, or it might require a new network to be built if there is still residual demand for natural gas. Either way, it is unlikely that off gas grid buildings will be able to benefit from a hydrogen supply. In these cases, dedicated heat pumps are likely to be the most obvious solution for decarbonisation. Off-gas grid homes, that might currently be supplied by oil or bottled gas, could represent the first type of homes to decarbonise heat (other than newly built homes which must have zero carbon heating systems installed from the outset). Support would need to be provided to ensure that these remote, off grid properties can achieve the requisite thermal performance to maximise heat pump efficiency and minimise energy bills. This is not likely to be a one size fits all package of options given the range of building types and ages, in which ill thought out “improvements” could negatively impact the building.

Biomass boilers are used to decarbonise heat in BOP and SOC in the near term before CCS enables better use of biomass in BECCS electricity and hydrogen plants. Some of these biomass boilers are assumed to already exist and are therefore not new installations. In these cases, the boilers are utilised and replaced at the end of their lifetimes. Biomass boilers are close to being net zero in ESME (some allowance is made for harvesting and transport emissions) and are quickly deployable, bridging the gap from the early 2020s to the mid-2030s when GHG targets become rapidly more stringent. Again, biomass boilers might be a useful option for off-gas grid homes to begin with. Eventually, as biomass is diverted into more useful applications (electricity and hydrogen production with CCS to produce negative emissions), these boilers will need to be replaced with alternative heating systems. For existing biomass boilers that may be reaching the end of life by 2030, replacement will be unavoidable and alternative low carbon options should be presented to the consumer at this time. For those boilers that were installed after 2020, reaching end of life by mid-2030s, the disruption associated with choosing an alternative heating system perhaps could be avoided with appropriate choices being offered and installed from the outset. With an assumed slower switch from gas boilers, the TEC scenario sees biomass being used to produce biomethane in the 2020s in an effort to decarbonise the gas being supplied to homes and businesses. In this scenario, biomass boilers no longer contribute to the direct supply of heat to buildings. What these scenarios show is the flexible role of biomass in decarbonising residential and non-domestic heat and the value in doing so prior to commercial scale CCS.

District heat is the third zero carbon energy vector for heating homes. District heat networks could be small, with just a few dwellings connected to a centralised heating system such as a community scale heat pump. Alternatively, it could involve connecting many residential buildings in a large urban conurbation which can make use of heat from nearby power stations.

One advantage of district heat networks is their ability to make use of heat recovered from thermal generation plants such as CCGTs and nuclear reactors, for example, specially designed small modular reactors are able to supply both electricity and district heat. Any future Scottish energy system will see no role for unabated gas plant or nuclear power. But there are other forms of thermal generation possible such as biomass fired generation, energy from waste and CCGTs all fitted with CCS infrastructure, and hydrogen turbines from which heat can be recovered for district heat networks. However, as has been discussed in the electricity generation section, these thermal generators tend to be used predominantly during the peak periods from the around 2040. Instead, Scottish district heat networks are fed mainly with heat from large scale heat pumps (Figure 3.18).

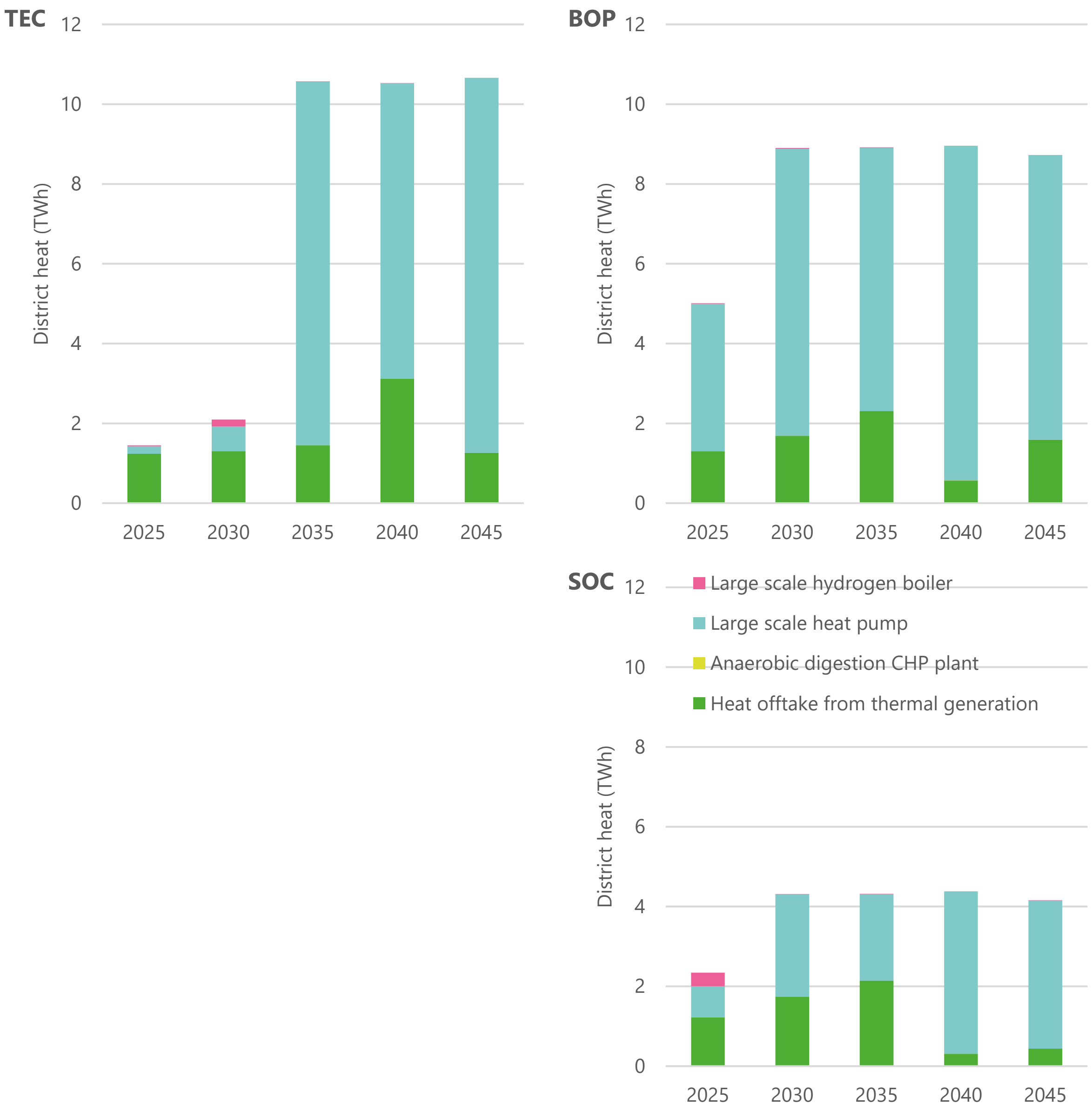

Figure 3.18: Supply of heat to Scottish district heat networks for TEC, BOP and SOC

The source of heat recovered from thermal generation changes over the pathway: early district heat networks are supplied by heat taken from unabated gas plants. By the 2030s, abated CCGTs and hydrogen turbines operating throughout the year (as discussed above) are able to support further rollout of district heat networks. By the 2040s, as these types of thermal generation plants operate in a peaking capacity, heat supply to district heat by these means decreases. Energy from waste plants with CCS are able to supply some heat but by and large, heat networks have shifted to large scale heat pump systems with large hydrogen boilers providing back-up during peak demand periods.

In ESME, unlike heat pumps, which require homes to meet a minimum level of thermal performance, heat networks are able to supply buildings which may be difficult or costly to retrofit building fabric improvements. The SOC scenario not only has a lower overall energy demand, but the overall thermal performance of the Scottish housing stock is higher than the other scenarios as an extensive programme of whole-building retrofit is rolled out. For these two reasons, fewer homes are connected to district heat compared to TEC ad BOP.

3.6.4 Transport

Cars

Car travel is the dominant form of transport in ESME, as such decarbonisation of the transport sector is heavily dependent on decarbonisation of car travel either by switching to zero carbon vehicles or forms of active travel such as walking and cycling.

Decarbonisation of car travel is driven strongly by the ban on new sales of internal combustion engine (ICE) cars by 2030 in line with UK legislation. Figure 3.19 shows the impact this has on the number of car miles powered by liquid fossil fuels.

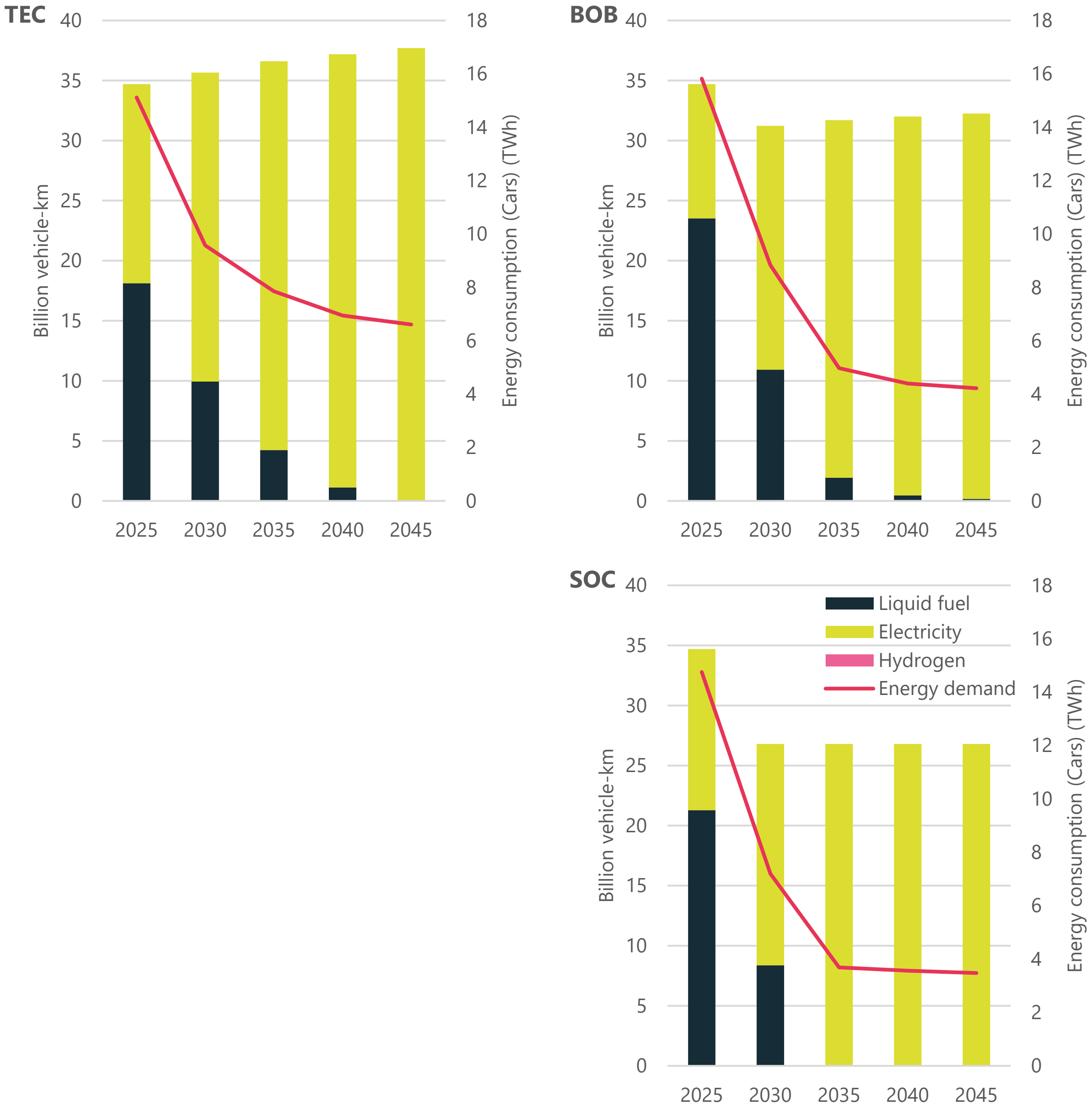

Figure 3.19: Breakdown of vehicle-km travelled by energy vector and total energy consumption associated with car travel in Scotland for TEC, BOP and SOC

Electric vehicles (EVs) are the dominant option for car decarbonisation with no hydrogen cars on the road. Hydrogen cars would increase the demand for hydrogen, either leading to higher production volumes, or diverting hydrogen from other sectors (e.g. industry or heating). In ESME, the value of hydrogen seems to be both in its flexibility, being able to supply peak loads, and as a zero-carbon energy vector able to decarbonise sectors that face different challenges (e.g. heavy-duty vehicles and industry). In parts of the energy system that have a range of zero-carbon technology options, hydrogen may not feature, or feature only in a peaking capacity. Car travel can be readily decarbonised with electricity which is zero carbon and can be generated in abundance. It also makes sense to avoid unnecessary efficiency losses associated with converting electricity into hydrogen.

Electric cars are more efficient than ICEs, indicated by the falling energy consumption associated with car travel (red line in the above charts). This is true even in TEC, in which the miles travelled by car are assumed to increase throughout the pathway. SOC assumes a 20% fall in miles travelled by car by 2030 relative to 2019 (pre-COVID) demand. Along with the 2030 ICE ban, this allows car travel to be entirely decarbonised by 2035.

In TEC and BOP, with higher car travel demand, decarbonisation takes a little longer but reaches net zero by 2045. It is also important to remember that TEC and BOP have higher biomass availability and engineered GHG removal capacity. This generates emissions headroom in the energy system, which can allow some sectors to reduce the rate of decarbonisation (see Box 2 below for an explanation of emissions headroom). Car travel is one such example, where plug-in hybrid vehicles (PHEVs) are permissible into the 2040s (although a ban on new PHEV sales comes into force in 2035). Whether PHEVs will in reality feature in the energy system of the 2030s/40s is yet to be seen.

Heavy goods vehicles

In these scenarios, electric powertrains are also used to decarbonise road freight. Figure 3.20 shows the majority of tonne-km were delivered using electric powertrains. The full transition from conventional HGVs occurs by 2035 The majority of HGVs are full electric but some use hydrogen in a fuel cell to extend the range of the battery. The deployment of these fuel cell range extended vehicles depends on the availability of hydrogen. In TEC, they can be deployed as early as 2030, using imported hydrogen from ROUK initially, but then Scottish hydrogen once CCS enables mass production. In BOP and SOC, hydrogen is in more limited supply and tends to be reserved for other applications such as industry and heating. Other options for low carbon HGVs such as hydrogen or natural gas fuelled HGVs may feature in other modelled scenarios subject to different assumptions. Hydrogen fuel cell HGVs are being developed along with hydrogen combustion engines (DAF, 2022) with a number of manufacturers collaborating to accelerate mass market rollout of hydrogen-fuelled trucks (H2Accelerate, 2021).

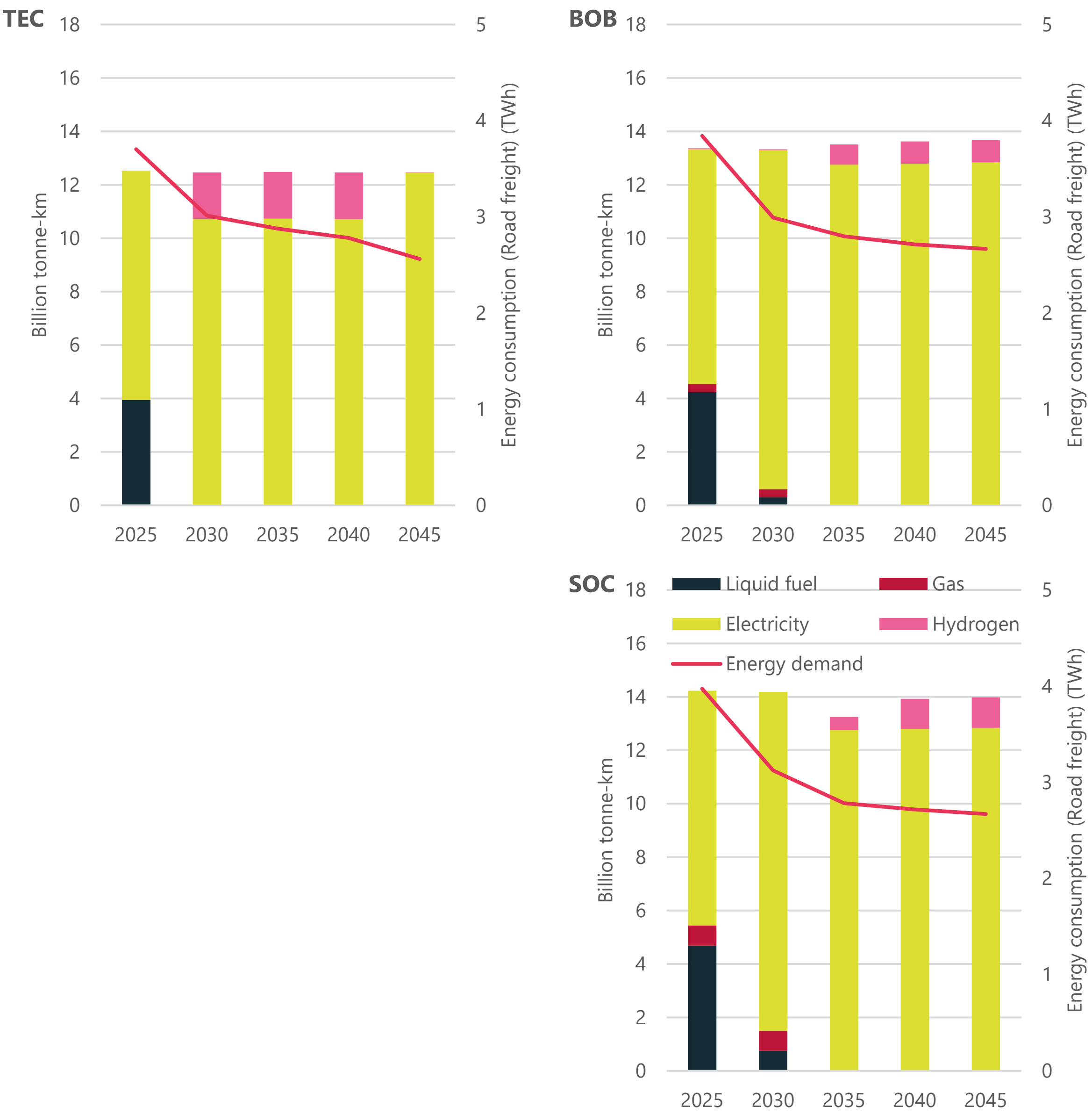

Figure 3.20: Breakdown of tonne-km travelled by energy vector and total energy consumption associated with road freight in Scotland for TEC, BOP and SOC

Other heavy-duty vehicles

In ESME, other heavy-duty vehicles include buses, off-road mobile machinery including construction vehicles and agricultural vehicles[6].

In all three scenarios modelled, the decarbonisation of buses is driven by the target for new buses to be zero emission from 2025. ESME has a range of options to decarbonise bus travel including a number of hybrid options and the use of natural gas. In terms of zero carbon options, as specified in the relevant target, hydrogen fuel cell and battery electric are the only options in the model. In all three scenarios, zero carbon buses are overwhelmingly battery electric. However, it should be noted that hydrogen buses have been tested and are currently in operation in Aberdeen funded by two projects: High V.LO-City and HyTransit.

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[6] Note that emissions associated with off-road mobile machinery are assigned to industry and agricultural vehicle emissions assigned to agriculture

In SOC and BOP, people are assumed to increase their use of buses as they reduce dependence on car travel. This is alongside increasing active travel modes such as walking and cycling.

A number of low and zero carbon options for off-road machinery exist in ESME including battery electric and hybrid hydrogen-electric powertrains. In the scenarios presented, battery electric options dominate although there is a strong role for hydrogen-electric hybrids. However, both options are not available until 2045. Agricultural vehicles decarbonise earlier with hybrid ICE powertrains being adopted from the mid-2020s to the mid-2040s. As the net zero 2045 target approaches, battery electric and hydrogen-electric hybrid farm vehicles are also deployed at scale.

Rail

Passenger rail demand in ESME is split between diesel and electric trains. The split between diesel and electric is not a model choice but rather an exogenous input. In these scenarios, it is assumed that all passenger rail in Scotland will be electrified by 2035. In reality, hydrogen presents another option for decarbonising rail and might be more appropriate in sections of track that are costly or difficult to electrify.

Shipping

Shipping is an important source of emissions in the Scottish energy system. There are few suitable technology options for maritime decarbonisation before 2045 in ESME other than dual fuel options running on natural gas and liquid fuel. However, in 2045, shipping is able to reduce emissions substantially using hydrogen. These ships can either use stored hydrogen, or they can use ammonia, which has a higher energy density (useful to minimise storage volumes) and can be utilised by fuel cells or internal combustion engines.

The Zero Emission Shipping Mission Roadmap (Zero-Emission Shipping Mission, 2022) states that commercially viable zero emission ocean-going vessels are needed by 2030 in order to set international shipping on an ambitious zero emission trajectory. This is 15 years ahead of when ESME is able to start deploying ammonia vessels and represents tremendous ambition by the sector. The target outlined in the roadmap is for at least 200 ships across major deep-sea shipping routes to be fuelled by zero carbon fuels by 2030. Fuel options that are mentioned include ammonia, hydrogen or biofuels.

Aviation

In the current version of ESME there are very few options for ESME to decarbonise aviation. Available options include biofuels to use in aircraft and early retirement of old aircraft in preference of newer more efficient models. Emissions for aviation can also be eliminated by reducing the demand for air travel as in the SOC and BOP scenarios. However, air travel demand is an exogenous input meaning that the model is unable to make changes to demand in an effort to reduce emissions – demand must be set by the user at the outset.

There is work being done to explore options for low and zero carbon flight compatible with UK aviation's commitment to net zero by 2050. Options being discussed include electric and hydrogen-powered flight and sustainable aviation fuels[7]. On top of this is the option for the aviation sector to fund carbon removal.

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[7] Sustainable aviation fuels (SAF) are produced from waste oils, agricultural residues or waste carbon rich gases. Whilst they do emit CO_2 when combusted, they offer overall emission savings compared to fossil derived aviation fuels.

3.6.5 Industry

Industrial decarbonisation is achieved through fuel switching away from fossil fuels and capturing CO_2 from energy and industrial processes.

Industry in ESME

In ESME, the use of energy in industry is segmented into nine sectors based on a combination of sector conventions from the Digest of UK Energy Statistics (DUKES) (BEIS, 2021) and from Energy Consumption in the UK (ECUK) (BEIS, 2022). Although "Cement, ceramics, glass and lime" is not treated as a separate sector in *DUKES*, it is treated as a distinct sector in ESME because it is a major energy intensive industry in the UK with potential for sector-specific carbon abatement technologies. Below is the list of industry sectors represented in ESME:

- Iron and steel
- Chemicals
- Metal products and machines
- Food, drink and tobacco
- Paper, printing and publishing
- Cement, ceramics and glass
- Refineries
- Other (includes industries such as textiles and rubber/plastic products)

Energy use in each industrial sector is broken down into six generic categories representing high level industrial processes:

- High temperature processes
- Low temperature processes
- Drying and separating
- Motors
- Space heating
- Other

Energy demand for each process is given relative to 2010. Hence in 2010 the total UK demand for every process is unity. In later years the demand for each process increases or decreases according to two factors:

I. Sector / process output relative to 2010, and
II. Sector / process energy intensity relative to 2010.

The trends in these two factors are set exogenously to the ESME model.

Energy demand for each process is regionalised based on the regional split of UK gross value added (GVA) associated with each of the industrial sectors for historic years. These splits are maintained for future years out to 2050. Results presented in this report are for aggregated industry (i.e. not broken down by sector/process) in ESME's Scotland region.

Modelling results for industry in Scotland

Figure 3.21 shows the amount of energy consumed in Scottish industry broken down by energy vector. The general trend observable in all scenarios is a move away from solid and liquid fossil fuels, and natural gas to hydrogen and electricity.

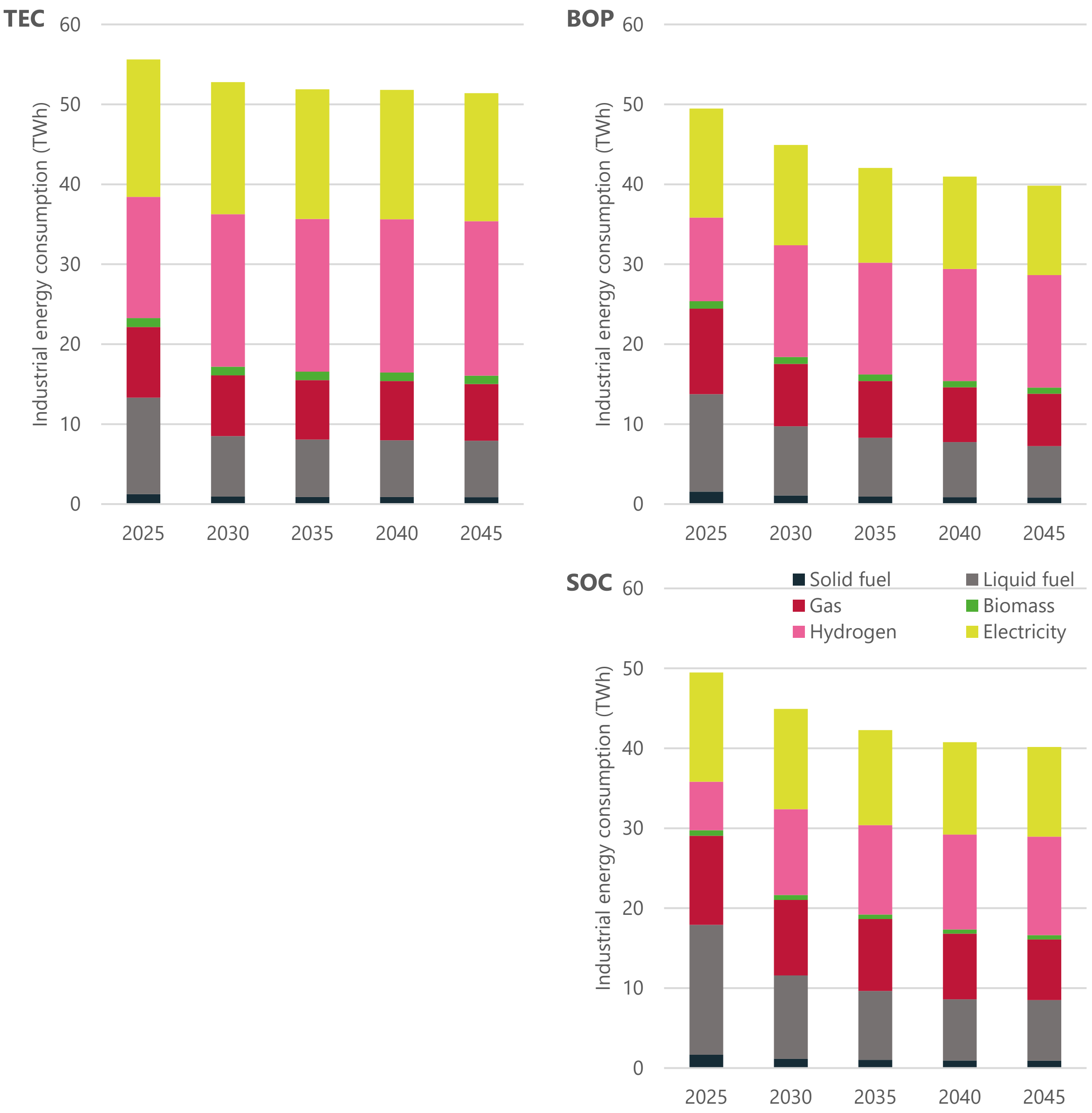

Figure 3.21: Industrial energy consumption in Scotland for TEC, BOP and SOC

There is a large increase in hydrogen consumption from 2025 to 2030 driven primarily by the 75% emissions reduction target coming into force in 2030 (prior to mass rollout of other low carbon options across the energy system). The hydrogen switch levels off post-2030 as other decarbonisation options (such as CCS and electrification of heat and transport) are rolled out at commercial scale. In ESME, these other options contribute to an energy system with a lower overall system cost vs. continuing to produce hydrogen to fuel further switching in industry. In reality, industry may struggle to achieve the level of hydrogen switching suggested in the modelling by 2030 given the nascency of the hydrogen market. Alternative options and strategies might be adopted more readily, but the extent of emissions reductions achievable in industry will determine what level of decarbonisation is needed from other aspects of the energy system. The results presented here are for just three illustrative scenarios. Other scenarios, with slower rates of industrial decarbonisation are also possible but will require greater action in transport and heating in order for emissions target to be met. This could be considered more challenging than a coordinated and targeted effort by major industrial emitters.

Total energy consumption by Scottish industry decreases over time in all three scenarios presented here. This is a result of the energy demand projections assumed in the model which as stated above include both assumptions about industrial output and energy intensity of industrial processes (i.e. energy efficiency improvements over time). BOP and SOC are lower energy demand scenarios versus TEC and the industrial energy demand case used assumes a shift away from heavy industries such as iron and steel. However, it should be noted that this is just one justification for lower energy demand in industry and there are perhaps others that are consistent with a thriving heavy industries sector. ESME does not have sight of the reasons underlying energy demand projections but simply constructs an energy system based on the input values provided by the modeller.

Residual fossil fuel exists as a result of the underlying assumptions in ESME. Industrial fuel switching is informed by an extensive piece of analysis carried out by UKERC, which maintains that there are challenges to wholesale shift away from fossil fuels in some parts of industry. Work continues to be done on this area and as evidence about how to overcome technical barriers emerges, is likely to change the extent to which industry can decarbonise in ESME.

Industrial emissions in TEC are highest partly as a result of higher overall energy demand. BOP and SOC have the same assumption around industrial energy demand and yet BOP industrial emission remain higher. This is likely due to emissions headroom created by negative emissions and direct air capture enabling a reduction in the industrial decarbonisation necessary to achieve GHG targets. SOC does not have these options to the same degree and so industry needs to do more to curb emissions.

Box 2: Emissions headroom

Negative emissions delivered by bioenergy with carbon capture and storage and greenhouse gas removal options (engineered or nature-based) create emissions headroom.

The concept of emissions headroom is quite important in least-cost optimisation, whole energy system models like ESME. By having sight of all sectors in an energy system, ESME is able to optimise the level of decarbonisation in each. Emissions headroom might be more easily or cost-effectively created in one sector to alleviate the pressure to decarbonise in another more costly sector. In this way, ESME is able to design an energy system that is compatible with a Net Zero UK without each individual sector needing to be an absolute (or even net) zero emitter. The implication is that some sectors may well be net negative and/or non-energy sectors such as land use may act as net carbon sinks.

If negative emissions can be generated somewhere in the system, then these models will pull back decarbonisation in the more difficult/costly sectors – there is no cost-incentive to over-deliver on overall GHG targets in such models. In some instances constraints might lead to over-delivery on targets but not without increasing the cost of the system. A key feature of least cost optimisers is that constraints increase costs.

All industrial sub-sectors see some decarbonisation, in particular there are a large number of industries that are not categorised in the main sub-sectors and are classified as “other”. In terms of energy demand, the other category (includes industries producing textiles and rubber/plastic products amongst others) is the largest and sees the greatest level of decarbonisation. The industries included in this classification could belong to, or be in close proximity to, the industrial cluster at Grangemouth. In this case, they could well take advantage of any hydrogen or CCS network installed here. On the other hand, these industries could be dispersed sites near to population centres again perhaps being able to take advantage of hydrogen networks. The final possibility is that they are remotely located for example distilleries located across the mainland of Scotland and the islands. These sites are perhaps more likely to find tapping into hydrogen or CCS networks more of an obstacle. In these instances, electricity or even natural gas might be the solution to reduce emissions. Chemicals and refineries see the greatest level of decarbonisation of the main industrial subsectors. A hydrogen switch is the main reason for this along with general energy efficiency measures.

3.7 Costing the transition

3.7.1 Financial assumptions and definitions

Capital cost

This is based on cost estimates for nth of a kind. Costs include, where relevant: EPC cost, infrastructure connection costs, pre-licensing costs, technical and design costs, licensing costs and public inquiry costs. Contingency costs are included but would normally be minimal for nth of a kind deployment. Land purchase costs and financing charges, such as interest during construction, are excluded.

Operating cost

Two components of operating cost are included:

- Fixed costs: Costs such as operation and maintenance costs which are incurred per year regardless of level of usage. [NB fuel costs are not included]
- Variable costs: Costs such as operation and maintenance costs which are in proportion to the level of usage. [NB fuel costs and balancing costs are not included]

Note that costs are used in ESME, not retail prices. Consequently, the cost data used in the model excludes taxes, levies, subsidies and similar.

Cost of capital

An investment rate of 8% (real) is assumed for the cost of capital for all technologies. This rate is used when annualising capital costs over the lifetime of a technology and when calculating the cost of interest during construction.

For the purposes of this analysis, the cost of capital does not change between technologies. In reality developer WACC relates to project and technology risk and will depend strongly upon the policy environment at the time. This uplifts the effective investment cost for risky projects relative to those at a lower risk.

Policy-influenced risk mitigation has not been assumed in the long-term in this analysis. Therefore, a simplifying assumption of a flat real technology discount rate of 8% is used in ESME analysis. However, short-term technology deployment will clearly be reflective of current policy (e.g. wind CfDs). This is included in modelling through forced deployment of technologies in pipeline and relevant statutory targets applied in each scenario.

Given how sensitive the overall cost of transition can be to cost of capital, it is important for policies to be designed and implemented to reduce the cost of capital demanded by private investors in clean, capex-heavy technologies.

Out of scope

Costs associated with meeting GHG targets (and other low carbon policies) are limited to those associated with designing an energy system compatible with these policies. Costs associated with not meeting GHG targets are not included in the assessment. It is important to bear in mind that global estimates of damages from failure to meet targets are far greater than the cost of mitigation. There are also a number of other co-benefits associated with decarbonisation such as improved air quality, biodiversity and health. A fully comprehensive assessment of the cost of meeting Net Zero would ideally include all of these factors.

3.7.2 Counterfactual scenario

Energy systems models like ESME produce cost-optimal pathways to meeting GHG targets under a range of different scenario specific assumptions. These models can be used to shed light on the cost of meeting GHG targets from an energy system perspective.

To do this, a counterfactual pathway is created that is not subject to GHG targets. The design of the counterfactual scenario can be quite subjective; for example, whether the counterfactual includes low carbon policies already committed to by Government is a decision for the modeller to make. In this analysis, the counterfactual scenario is the simplest interpretation i.e. no current or future low carbon policies are incorporated. This allows the cost of meeting targets for TEC, BOB and SOC to be evaluated on a purely techno-economic basis.

3.7.3 Comparative analysis of pathway costs

The counterfactual scenario described above serves as a benchmark against which the three net zero pathways are compared in terms of cost. The counterfactual scenario does not include GHG targets or other climate change policies; therefore, investment in low and zero carbon technologies is not necessary for the model to solve (although may occur if costs of such technologies are lower than their higher carbon counterparts). As a result, the absence of such constraints in a least cost optimiser model such as ESME will inevitably result in a lower cost system than one subject to climate change targets. However as mentioned above, the cost of not mitigating climate change is not included and in reality, is estimated to be much higher than a net zero transition.

The difference in four main costs (capital investment, infrastructure, operational and resource) between the three scenarios modelled and the counterfactual are show in Figure 3.22.

Figure 3.22: Capital investment (in power, buildings & heat, industry and transport sectors), infrastructure, operating (fixed and variable) and resource costs relative to counterfactual scenario for TEC, BOB and SOC

TEC, BOP and SOC are characterised by:

- Investment in capital-intensive energy system technologies.
- Investment in infrastructure required to support the transition (including CO_2 pipelines and storage and electricity/hydrogen distribution and transmission)
- Operating costs largely incurred by maintenance of offshore wind in the power sector (noticeably higher in TEC and BOP with high capacities of wind power forced in)
- Savings in resource costs as a result of much lower consumption of nuclear and fossil fuels in the three net zero pathways vs. the counterfactual

Technology innovation scenario

The TEC chart in Figure 3.22 shows the highest cost differences relative to the counterfactual. Investment in capital-intensive technologies such as on/offshore wind, electrolysis, heat pumps and electric vehicles (amongst others) are greatest source of difference compared to the counterfactual.

Overall investment (including in infrastructure) increases year on year throughout the 2020's in order to meet the 2030 GHG target and statutory targets related to on/offshore wind. After 2030, investment each year decrease as costs come down and much of the power and transport sector decarbonisation has occurred. However, annual investment from 2040 in new transport technologies, hydrogen production and hydrogen rollout in homes and non-domestic buildings increases to ensure the net zero target is met. A summary of the system costs is given in Table 3.2.

Table 3.2: Summary of system costs in TEC

Capital investment	*Transport:* Highest investment seen in the transport sector throughout the pathway (on average around half the investment each year throughout the pathway is in low carbon transport). This is mainly a result of the millions of cars switching from ICE to plug-in hybrid and electric. *Power & conversion:* Power & conversion (includes electricity and hydrogen production) sees the next highest level of investment throughout the pathway (on average 30-40% of the investment each year throughout the pathway). Most of this is a result of the high capacity of on and offshore wind installed from mid-2020s to 2045. Investment in hydrogen turbines also contributes. *Buildings & heat:* Highest investment in this sector is seen before 2030 as a result of building fabric improvement packages, heat pump and early hydrogen rollout and connection to DHNs. Continued rollout of hydrogen, heat pumps and connection to DHNs sees investment of around 10-15% of the total capital investment each year from 2035-2045. *Industry*: Lowest levels of investment in this sector on account of the overall capacity of technology switches made compared to the other sectors (e.g. vs. tens of GWs of low carbon electricity and hydrogen generation installed and millions of gas boilers and ICE vehicles replaced). Peak investment occurs in 2030s to fund a hydrogen switch and CCS rollout.
Infrastructure costs	Most of the investment in infrastructure is to support large quantities of wind generation. This includes transmission from offshore regions, distribution around Scotland and transmission to other parts of the UK. CO_2 networks and pipelines to offshore storage sites represent another source of investment in infrastructure to support direct air capture facilities and CCS networks in industry, hydrogen production and power.
Operating costs	Roughly 2/3 of the operating costs are associated with the power sector. This is predominantly associated with maintenance of offshore wind and other offshore renewables. The remaining 1/3 is attributed to the transport sector again related to maintenance of vehicles.
Resource costs	Resource costs decrease throughout the pathway as natural gas, solid and liquid fossil fuels are consumed less as a result of electrification of large parts of the energy system combined with a shift to district heat and hydrogen fuelled technologies too. Energy efficiency improvements in parts of transport and industry that see residual fossil fuel use also contribute to a reduction in consumption and resource costs. Resource cost savings are less than in the TEC scenario because BOP uses more natural gas to produce hydrogen.

Balanced options scenario

The BOP chart in Figure 3.22 shows the similar trends to the TEC chart i.e. high investment in capital-intensive technologies such as on/offshore wind, heat pumps and electric vehicles (amongst others). Resource cost savings are also apparent as fossil fuel reliance decreases through the pathway. However, savings are less compared to those experienced in the TEC scenario. This is because BOP produces more hydrogen than TEC, the majority of which is from natural gas reformation (with CCS).

There is a spike in investment in 2035 as a result of increased investment in the transport sector to replace ICEs and non-plug in hybrids with electric cars. This is likely to be an artefact of the modelling with existing ICE and non-plug-in hybrids reaching the end of life by 2035 and being replaced with EVs. In reality, sudden spikes in EV sales are only likely to happen as a result of policies such as ICE/hybrid scrappage schemes or approaching cut-off dates for incentive schemes (as was seen in roof-top photovoltaic installation rates as the feed in tariff cut-off date loomed in March 2019). A summary of the system costs is given in Table 3.3.

Table 3.3: Summary of system costs in BOP

Capital investment	*Transport:* Highest investment seen in the transport sector throughout the pathway (on average around half the investment each year throughout the pathway is in low carbon transport). This is mainly a result of the millions of cars switching from ICE to plug-in hybrid and electric. *Power & conversion:* Power & conversion (includes electricity and hydrogen production) sees the next highest level of investment throughout the pathway (on average 30-40% of the investment each year throughout the pathway). Most of this is a result of the high capacity of on and offshore wind installed from mid-2020s to 2045. Investment in hydrogen turbines also contributes as does blue hydrogen production. *Buildings & heat:* Highest investment in this sector is seen before 2030 as a result of building fabric improvement packages, heat pump and early hydrogen rollout and connection to DHNs. Continued rollout of hydrogen, heat pumps and connection to DHNs sees investment of around 20% of the total capital investment each year from 2035-2045. *Industry*: Lowest levels of investment in this sector on account of the overall capacity of technology switches made compared to the other sectors (e.g. vs. tens of GWs of low carbon electricity and hydrogen generation installed and millions of gas boilers and ICE vehicles replaced). Peak investment occurs in 2030s to fund a hydrogen switch and CCS rollout.
Infrastructure costs	Most of the investment in infrastructure is to support large quantities of wind generation. This includes transmission from offshore regions, distribution around Scotland and transmission to other parts of the UK. CO_2 networks and pipelines to offshore storage sites represent another source of investment in infrastructure to support direct air capture facilities and CCS networks in industry, hydrogen production and power.
Operating costs	Roughly 2/3 of the operating costs are associated with the power sector. This is predominantly associated with maintenance of offshore wind and other offshore renewables. The remaining 1/3 is attributed to the transport sector again related to maintenance of vehicles.
Resource costs	Resource costs decrease throughout the pathway as natural gas, solid and liquid fossil fuels are consumed less as a result of electrification of large parts of the energy system combined with a shift to district heat and hydrogen fuelled technologies too. Energy efficiency improvements in parts of transport and industry that see residual fossil fuel use also contribute to a reduction in consumption and resource costs.

Societal change scenario

The SOC chart in Figure 3.22 shows the lowest cost differences relative to the counterfactual. This is mainly a result of a more modestly sized power sector in SOC as on/offshore wind capacity targets are not imposed on this scenario. This also has knock-on effects on infrastructure and operating costs since large amounts of offshore transmission are not needed, nor is transmission of large quantities of electricity to ROUK (although some transmission is needed here to provide system balancing or supply and demand).

Generally, costs in SOC are lower as a result of this being a low energy demand scenario (relative to TEC and BOP). In ESME, energy demand is an exogenous input and reductions in demand represent cost savings since less capacity and infrastructure is needed to satisfy energy requirements. In reality, demand reduction may be associated with costs that are not captured in energy systems models such as consumer disruption or policy costs. A summary of the system costs is given in Table 3.4.

Table 3.4: Summary of system costs in SOC

Capital investment	*Transport:* Highest investment seen in the transport sector throughout the pathway (on average 40-60% of the investment each year throughout the pathway is in low carbon transport). This is mainly a result of the millions of cars switching from ICE to plug-in hybrid and electric. *Power & conversion:* Unlike TEC and BOP, capital investment in the SOC scenario is relatively low at ranging from 5-20% of total capital investment each year. This is on account of the more modestly sized power sector and comparatively low levels of hydrogen production. *Buildings & heat:* Investment in this sector is around 20-30% of total capital investment each year. as a result of building fabric improvement packages, heat pump and early hydrogen rollout and connection to DHNs. *Industry*: Lowest levels of investment in this sector on account of the overall capacity of technology switches made compared to the other sectors.
Infrastructure costs	Much lower levels of investment compared to TEC and BOP as a result of a less developed CCS network and smaller power sector. Most of the investment in infrastructure is to support wind generation. This includes transmission from offshore regions, distribution around Scotland and transmission to other parts of the UK (on a much smaller scale than in TEC and BOP but necessary for system balancing). CO_2 networks and pipelines to offshore storage sites represent another source of investment in infrastructure to support CCS networks in industry, hydrogen production and power.
Operating costs	The split of operating costs between power and transport sector is inverted in SOC compared to TEC and BOP with roughly 1/3 of the operating costs associated with the power sector. This is predominantly associated with maintenance of offshore wind and other offshore renewables. The remaining 2/3 is attributed to the transport sector again related to maintenance of vehicles.
Resource costs	Resource costs decrease throughout the pathway as natural gas, solid and liquid fossil fuels are consumed less as a result of electrification of large parts of the energy system combined with a shift to district heat and hydrogen fuelled technologies too. Energy efficiency improvements in parts of transport and industry that see residual fossil fuel use also contribute to a reduction in consumption and resource costs.

4. Conclusions

Four scenarios have been created to explore possible future energy systems in Scotland. The scenarios were designed to present a range of ways in which Scotland could transition the current energy system to one that is net zero by 2045. All of the scenarios were bound by UK and Scottish GHG targets, these include:

- UK carbon budgets (currently set in UK law up to 2037), leading to UK net-zero target date of 2050
- Scottish annual and interim targets (including 2030 target of 75% reduction in emissions from 1990 baseline), leading to Scottish net-zero target date of 2045

The scenarios aim to present options to help inform policy and encourage debate. They are not intended to be taken as fixed pathways Scotland should follow to meet GHG targets.

The four scenarios have been positioned on a framework that describes a range of technological innovation and societal change. The TEC scenario is characterised by high uptake of certain key technologies (e.g. offshore wind) in line with Scottish Government's maximum ambition. GHG removals are achieved by BECCS and direct air capture of CO_2. Scotland becomes a net exporter of both electricity and hydrogen. The impact on people's lives is assumed to be moderate in terms of adopting low carbon lifestyles (including reducing energy demand and changes in diet), but a degree of buy-in is necessary for low carbon technologies to be taken up to the extent needed.

SOC is positioned diametrically opposite to TEC in that people reduce their consumption of energy and their carbon footprints by adopting low carbon behaviours. These include reducing demand for heat, walking and cycling more, and eating diets low in red meat and dairy. Engineered removal of GHG does not feature in the scenario and biomass availability is low. Ambitious tree planting and peatland restoration rates combined with greener diets mean land use is a net sink of CO_2 by 2040. BOP lies somewhere between TEC and SOC, with some changes in behaviour taken up and some innovation in GHG removal technologies. The final, CORE scenario is unable to meet GHG targets because societal change and technology innovation is insufficient to allow this.

The key observations from the modelling results suggest:

- **Power sector decarbonisation is urgent in all of the scenarios**. Renewables will likely be the workhorse of any future Scottish power system, but urgent progress is needed on technologies like CCUS to provide firm back-up capacity.
- **Electricity and hydrogen are likely to be the two most important energy vectors** in a Net Zero Scotland regardless of the route to transition taken
  - Electricity is good for bulk supply of energy to all sectors of the energy system because it can be readily produced in abundance from low and zero carbon generators
  - Hydrogen is useful in supporting peak demands where meeting these loads with electricity would require high generating capacity and reinforcement of the grid
  - Baseload hydrogen supplies a limited set of sectors/processes that cannot be easily/cost-effectively electrified such as some industrial processes and shipping. In this context, we define baseload as a constant, 24/7 supply of an energy carrier. The capacity of such supply is typically aligned to minimum energy demand of an energy end-use within a sector in a typical period

    - Reserving hydrogen for supporting peak energy demand periods and a limited number of applications requiring baseload energy reduces the production volumes necessary which minimises overall cost of the energy system
- The ScotWind auction and ambitious policy targets for on and offshore wind capacity will lead to Scotland producing more electricity than it is likely to need even with increasing demand for electricity going forward. **Scotland will become a key provider of electricity for the UK** as a whole. Alternatively, Scotland could seek to export this electricity to other parts of Europe (not explored in this analysis) or use it to produce green hydrogen for domestic consumption or export elsewhere in the world.
- **Rapid electrification of residential and non-domestic heat is needed if reliance on gas boilers is to be reduced**
    - Heat pumps are a crucial technology to do this and might be installed in in off gas-grid homes and new builds to begin with but will need to be rolled out to the wider housing stock by 2030
- **Biomass boilers are an important bridging technology helping homes to decarbonise heat** almost overnight up until the mid-2030s when GHG targets see the quickest rate of change.
    - They make the best use of limited biomass supply in the near term before an increase in supply and combined use with CCS, at which time a more practical and effective use is in hydrogen production
- **Biomass is a tremendously valuable energy vector due to its ability to produce low carbon heat, electricity and hydrogen**. It becomes an important source of negative emissions when CCS is deployed on mass scale. By 2045, BECCS creates negative emissions in the order of 9mtCO_2 in TEC, 7mtCO_2 in BOP, 4mtCO_2 in SOC - enough to offset the majority of residual emissions from industry, agriculture and transport in all three scenarios
- **Industry and transport are key sources of residual energy system emissions** in 2045 with power and heating being entirely decarbonised. Advances in industrial decarbonisation such as strategies being explored by industrial clusters could reduce emissions further than is currently assumed in the modelling. This would reduce reliance on as yet unproven or risky technologies such as biomass gasification with CCS for hydrogen production, although this could be an important source of hydrogen that enables total industrial decarbonisation. Alternatively, it could mitigate the risk that the level of decarbonisation expected/needed in other sectors does not happen e.g. in the event of a stubborn second-hand ICE car market undermining the 2030 ban on new ICE sales, or decarbonisation of buildings/roll-out of heat pumps not being able to ramp up in time. Low/zero carbon industry and manufactured products could represent competitive advantage for Scottish industry in global markets that are under pressure from consumers to provide low carbon goods.
- **Non-energy sector emissions (e.g. peatlands, agriculture and other land uses) remain a major source of emissions throughout each pathway**. Reducing land use sector emissions by re/afforestation and restoring peatlands would remove CO_2 and improve bio-diversity as well as provide green spaces for people to enjoy but land use could still remain a net source of GHG emissions as in TEC and BOP. Reduction in agricultural emissions is likely to be necessary to make land use emissions net zero, or even net negative as in SOC. This will mean supporting farmers in adopting improved agricultural practices such as waste and

manure management and breeding of livestock with fewer GHG emissions. Shifts in diet away from red meat and dairy will also play a big role in reducing emissions from livestock and can free up land used for grazing for forestry and bioenergy crops.

- **Biomass gasification is a key technology deployed in all three scenarios to produce hydrogen**. CCS is a key enabler of mass roll-out of this technology as well as an ample supply of biomass. The value of using biomass to produce hydrogen lies in the negative emissions created as well as a crucial zero carbon energy vector.
- **Decarbonisation of transport is driven by the legislated ban on new ICE sales**. This leads to the vehicle fleet being overwhelmingly electric. EVs replace cars at the end of their lifetimes (assumed 13years) and the model has perfect foresight to plan this. In reality, people may rush to purchase ICE cars before the ban comes into force keeping a number of ICEs on the road past 2030. Alternatively, people may choose to keep their ICE cars for longer than the lifetime assumed in the modelling. This would mean older, less efficient vehicles on the road too. There needs to be a concerted effort to encourage people to buy EVs (alleviate fears about battery life and range, provide evidence about lifetime of second-hand EVs and ensure necessary infrastructure exists and is easy to find) and prevent a rush to purchases ICEs before the ban. Schemes to get old vehicles off the road such as scrappage schemes might well be important considerations.
- TEC demonstrates how with innovation in technology (including policies and business models to support adoption) GHG targets can be met with relatively moderate impact on people's lifestyles. SOC on the other hand shows what is possible when the population get engaged with the climate emergency by reducing energy demand and changing diets. Encouraging and persuading people to make these changes to their lifestyles could be profoundly difficult and Government are unlikely to want to create legislation that prohibits certain activities. So, investment in technology hedges against a disengaged population as is represented in BOP. It is likely that if the investment and innovation seen in TEC is combined with the level of engagement seen in SOC, then Scotland will be able to go beyond its current GHG reduction targets.

5. References

BEIS. (2021). *Digest of UK Energy Statistics (DUKES)*. Retrieved from gov.uk: https://www.gov.uk/government/collections/digest-of-uk-energy-statistics-dukes

BEIS. (2022). *Energy consumption in the UK*. Retrieved from gov.uk: https://www.gov.uk/government/statistics/energy-consumption-in-the-uk-2021

CCC. (2020). *The Sixth Carbon Budget.* London: CCC. Retrieved from https://www.theccc.org.uk/publication/sixth-carbon-budget/

CEH. (2017). *Implementation of Emissions Inventory for UK Peatlands.* Bangor: Centre for Ecology & Hydrology. Retrieved from https://uk-air.defra.gov.uk/assets/documents/reports/cat07/1904111135_UK_peatland_GHG_emissions.pdf

DAF. (2022). *Hydrogen an interestion option for the future*. Retrieved May 13, 2022, from daf: https://www.daf.co.uk/en-gb/trucks/alternative-fuels-and-drivelines/hydrogen

Element Energy. (2020). *Deep Decarbonisation Pathways for Scottish Industries.* The Scottish Government. Retrieved from https://www.gov.scot/publications/deep-decarbonisation-pathways-scottish-industries/documents/

H2Accelerate. (2021). *Accelerating the uptake of green hydrogen for trucking*. Retrieved May 13, 2022, from H2Accelerate: https://h2accelerate.eu/

National Grid. (2021). *Scottish Boundaries*. Retrieved May 12, 2022, from National Grid ESO: https://www.nationalgrideso.com/research-publications/etys/electricity-transmission-network-requirements/scottish-boundaries

SSE. (2022). *NEW GORDONBUSH PROJECT STEPS UP SSE'S GREEN HYDROGEN PUSH*. Retrieved May 10th, 2022, from SSE: https://www.sse.com/news-and-views/2022/04/new-gordonbush-project-steps-up-sse-s-green-hydrogen-push/

Zero-Emission Shipping Mission. (2022). *Industry roadmap for zero emission shipping.*

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Appendix I – Background Analysis

As an early input to the project, Scottish Government provided an overview of the existing **Scottish net zero policy** landscape. This is shown below.

In addition, an **outline scenario framework** was proposed by ESC and agreed with Scottish Government. The rationale behind that framework is summarised here.

This was accompanied by a **literature review**, to elicit key themes and assumptions to be tested within the four scenarios.

Scottish Government Net Zero Policy

This overview of the Scottish net zero policy landscape is based on the following core documents:

- 2017 Energy Strategy
- 2018 Climate Change Plan (2018-2032)
- Climate Change (Emissions Reductions Targets) (Scotland) Act 2019, which amends the Climate Change (Scotland) Act 2009
- 2020 Update to the Climate Change Plan (CCPu) *(the primary source)*

Further literature referred to includes:

- Heat Networks (Scotland) Act
- *Draft* Heat in Buildings Strategy
- Hydrogen Policy Statement
- National Transport Policy 2

Statutory Targets

2030	Deliver at least 6TWh of heat demand via **heat networks** (2.6TWh heat supplied by DHN by 2027)
2030	**75%** GHG reduction v 1990
2040	**90%** GHG reduction v 1990
2040	Remove fuel poverty, as far as is reasonably possible by 2040 and, in any case, ensure that by that date no more than 5% of households are in FP (24.6% in 2019)
2045	**Net Zero** GHG emissions

All other years from now to net-zero: annual emissions reduction targets (full list on Scottish Government website)

Non-statutory Targets

2021	Equivalent of 100% of Scotland’s gross **electricity consumption** to come from renewables
2023	All Local Authorities to develop a Local Heat and Energy Efficiency Strategy (LHEES)
2024	Ensure that the majority of **new buses** purchased are zero emission
2024	All **new homes** to use zero emission heating systems
2029	Zero carbon **electricity generation**
2030	Decarbonise **almost all off-gas-grid** properties,

	at least **1 million on gas grid** domestic properties and
	at least **50,000 non-domestic** properties
2030	Ensure that the equivalent of **at least 50% of energy**, across **heat, transport and electricity** comes from **renewable** sources (21.1% in 2018)
2030	Remove the need for petrol and diesel **cars and vans**
	Reduce **car kilometres** by 20% (vs 2019)
2030	At least **5GW of hydrogen** production capacity by 2030
2030	Increase **energy productivity** by 30% compared with 2015 (up by 1.6% in 2018)
2030	2GW of renewable capacity in community ownership
2030	Ambition for **8-11GW offshore wind** capacity
2035	Remove the need for new petrol and diesel **heavy vehicles**
2040	“Work to” decarbonise scheduled flights within Scotland

Outline Scenario Framework

From the outset of the project ESC provisionally suggested a 2x2 matrix based on the key uncertainties of **technological** and **societal** change, having used this approach successfully in our own UK-wide net zero scenarios.

The Climate Change Committee (CCC) have since used the same framing for their Sixth Carbon Budget scenarios, further strengthening the rationale for adoption by Scottish Government.

Following a briefing on the relevant policy landscape by Scottish Government, a literature review, and several expert interviews, we were satisfied that the original framework recommendation provided the most suitable basis for exploring the challenges and opportunities for Scotland in meeting its carbon targets.

In this section we provide some context behind the framework.

ESC’s Innovating Net Zero

In March 2020, ESC published its flagship report Innovating to Net Zero (ITNZ) The analysis involved a comprehensive update of our Energy System Modelling Environment (ESME) to consider net-zero, which had been continuously developed over ten years to explore pathways to a UK 80% target.

Initially, when the ESME carbon trajectory was set to net zero, the model was unable to find a pathway that could meet the target. To reach net zero, the dataset had to be enhanced in line with one or more of the following strategies:

- Reducing the **demand** for hard-to-treat activities
- Adding new low carbon **technology** options for these activities
- Expanding negative emissions **offsetting** potential

Accordingly, building on the CCC net zero advice to UK Government, we set out six ‘speculative measures’ that could be deployed in some combination to ensure ESME could achieve net zero. These were (compared to the standard ESME assumptions):

- Slowing aviation demand growth to 20% (vs 60%) from 2005-2050
- Reducing consumption of red meat/dairy by 50% (vs 20%) from 2020-2050
- Increasing afforestation to sequester 33 $MtCO_2$ (vs 22) annually by 2050

- Increasing UK biomass to 140 TWh (vs 120) annual resource by 2050
- Carbon capture and storage (CCS) capture rates of 99% (vs 95%) for certain techs
- Allowing UK-wide direct air capture (DAC) of 25 $MtCO_2$ (vs 1) annually by 2050

Instead of using all speculative measures, we constructed a 2x2 scenario framework based on the axes of further **technological** and **societal** change, allocating the speculative measures above to the most suitable axis. This scenario framework enabled us to simultaneously:

- Avoid a sense of complacency by retaining a 'failure' scenario
- Provide some hope that, by pushing on all fronts, we could potentially over-deliver
- Show that even a limited mix of speculative measures could achieve the target
- Explore two such combinations through the grand themes of technology and society.

Although land use change could have been treated as a third axis in its own right, creating a 2x2x2 scenario cube, managing such an extensive range of alternative scenarios can begin to obscure the core insights. Rather, we opted to place the land use measures into the socio-technical framing by positing that afforestation was more likely to be associated with societal engagement and increased demand for access to green/wild spaces, while biomass production was better associated with technological change, as part of an energy-industry pull on sustainable resources.

Figure A.1 illustrates the scenario matrix as applied in Innovating to Net Zero. The vertical axis represents a shift from the standard ESME assumptions to the further technological change ('TEC') dataset. This includes direct air capture, high CCS capture rates and high biomass production.

BOB represents the 'Best of Both" technological and societal changes. We used this quadrant to explore more cost-effective ways to achieve the same carbon targets as TEC and SOC.

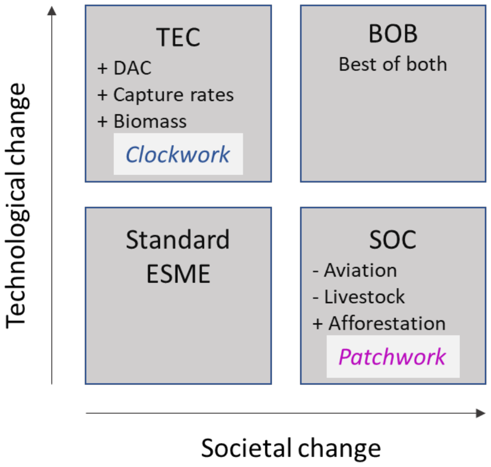

Figure A.1: ESC's Innovating to Net Zero (UK) scenario framework, showing the four quadrants of: standard ESME assumptions (limited to 96% emissions reduction), further technological change (TEC), further societal change (SOC) and the best of both (BOP). ESC's Clockwork and Patchwork scenarios are based on the TEC and SOC assumption sets respectively, used in the ESC ITNZ report.

CCC's Sixth Carbon Budget scenarios

The ITNZ analysis explored the 2050 UK net zero target, but at the time, there was a lack of clarity on the implications for interim carbon budgets. In December 2020, the Climate Change Committee (CCC) published its Sixth Carbon Budget (CB6) advice to Government (including specific advice to the Scottish Government).

The CB6 report included a scenario framework (see Figure A.2) based on the two dimensions of behavioural change and improvements in technology costs and performance providing further confidence of the suitability of this approach.

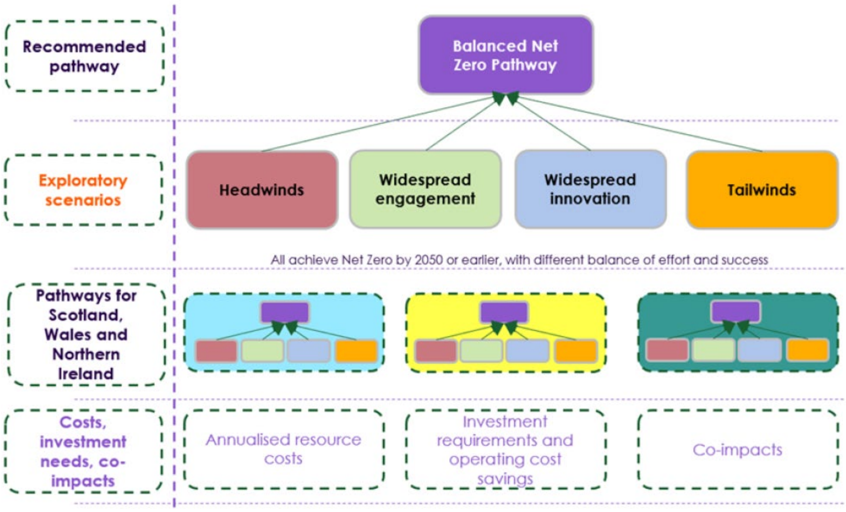

Figure A.2: CCC Scenario framework, reproduced from Fig 1.2 in The Sixth Carbon Budget (2020) report

The CCC CB6 scenarios can be summarised as follows:

- **Headwinds** lacks progress on either dimension
- **Widespread Innovation** includes further technological ambition
- **Widespread Engagement** includes further behavioural change
- **Tailwinds** includes further technological and behavioural change (and achieves Net Zero before 2050)

National Grid ESO's FES scenarios

Each year, National Grid ESO release their Future Energy Scenarios which outline a number of credible energy futures for the development of the UK energy system. For FES 2020, a new scenarios framework was adopted around which their future scenarios are formed. This is based on level of societal change in one axis and speed of decarbonisation in the other, as shown in Figure A.3.

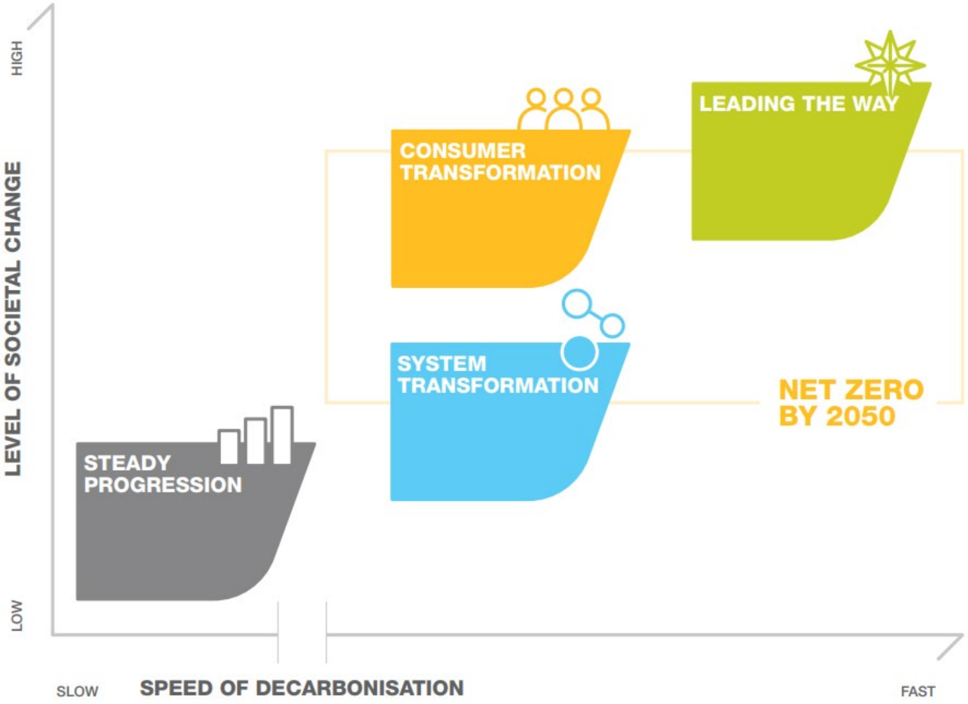

Figure A.3: National Grid ESO Future Energy Scenario framework. From FES 2020 report

- **Steady Progression** represents the slowest credible decarbonisation and doesn't meet the target of Net Zero by 2050.
- **System Transformation** represents greater system level changes, with more emphasis on solutions such as hydrogen for heating and supply side flexibility. This scenario meets the 2050 Net Zero target.
- **Consumer Transformation** represents greater emphasis on consumer behaviour change, greater energy efficiency improvements and demand side flexibility. This scenario also meets the 2050 Net Zero target.
- **Leading the Way** represents the fastest credible decarbonisation with a combination of significant lifestyle change and energy system transformation. This scenario reaches Net Zero before 2050.

This scenario framework has also been adopted by distribution networks in the development of their Distribution Future Energy Scenarios (DFES).

Wider Literature Review

A scoping study of evidence and material to assist in the development of a scenario framework began with identification of 47 papers, reports and articles. Of these, 33 were excluded on the basis of relevance (common reasons for exclusion included the age of the article, lack of specificity for Scotland, or the research was too narrowly focused to be of use in scenario design).

Of the fourteen studies selected for closer review, ten involved some degree of modelling or scenario analysis. From the review, three themes emerged:

1. Scotland's progress towards meeting emission reduction targets
2. Key technologies needed for transition to a low carbon energy system
3. The role of land use and greenhouse gas removals in the transition.

Scotland’s progress towards meeting emission targets

Scotland has demonstrated an impressive reduction in GHG emissions from 1990, with emissions falling by 45% from 1990 to 2018 (NAEI, 2021)[8]. The majority of savings are a result of tremendous effort in the power sector: In 2019, 90% of gross electricity produced was from renewable sources and coal has been eliminated from the generation mix. There remains one large gas-fired power station (1.2GW) at Peterhead. As a result, Scotland is a net exporter of low carbon electricity to the rest of GB.

Additional effort has also been made in the waste sector. From 2008 to 2018, emissions from waste (in the form of methane) fell by 46%. This is a result of an overall reduction in the total amount of waste produced, increased rates of recycling and less biodegradable waste placed in landfill (CCC, 2020a)

The difficulty will be in continuing to deliver emissions reductions. Remaining emissions savings to be had from the power sector are small, which means more needs to be done in the remaining sectors of the economy (CCC, 2020a; WWF, 2019).

The CCC has stated the challenge associated with meeting Scotland's 2030 emissions reduction target of 75% relative to 1990 levels (CCC, 2020b). None of the five scenarios explored by the CCC were able to deliver this level of reduction in the timeframe, with the most optimistic scenario (Tailwinds) only reaching 69% by 2030. CCC's balanced pathway was able to achieve 75% reduction by 2035 but even this scenario is pushing the bounds of technical feasibility suggesting the 2030 target is likely to be very difficult to achieve. Nonetheless, CCC do not advise that the statutory target be revised in anyway but offer suggestions of how this target could be achieved including:

- Earlier start to engineered greenhouse gas removals
- Early decarbonisation of the Grangemouth cluster
- Accelerated scrappage of high-carbon assets
- Additional retrofit of hybrid heat pumps

Key technologies and areas of focus

Further emissions savings from the Scottish power sector will be challenging. Nevertheless, increasing the amount of renewable generation would be of benefit as Scotland moves away from gas and nuclear. As a net exporter of low carbon electricity to the rest of the UK, this would help the UK as a whole towards meeting carbon targets. However, emissions savings will be needed from the remaining sectors of the economy: industry, transport, buildings & heat, land use and agriculture.

Compared to the UK average, Scotland has a higher proportion of homes that are not connected to the gas grid (CCC, 2020c). Therefore, there needs to be heating solutions for these homes that do not rely on connection to a decarbonised gas network (which could supply low carbon hydrogen or biomethane).

Favourable economics means that heat pump roll out in Scotland is likely to be targeted to off gas grid homes (as well as new build properties) (SPEN, 2020). Analysis conducted for SP Energy Networks shows a range of possible heat pump rollout rates for Scotland with an upper estimate of 500,000 by 2030 and 1.85 million by 2050. Indeed, by 2050, analysis by Vivid Economics suggests at least 90% of buildings in Scotland will need to be supplied with some form of low carbon heat (WWF, 2019). This would imply installation rates approaching 70,000 homes per year, which is a substantial increase from the 20,000 gas boilers installed each year currently.

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[8] 2019 data is now available here: Scottish Greenhouse Gas statistics: 1990-2019 - gov.scot (www.gov.scot). This was released after the background analysis was completed and modelling was underway.

As well as supplying low carbon heat, effort should be made in reducing overall demand by improving the thermal efficiency of the housing stock. The Existing Homes Alliance (cited in WWF, 2019) state that by 2030, all homes should be at least EPC C, which will require 80,000 energy efficiency retrofits per year (Existing Home Alliance, 2019).

Industry in Scotland currently emits 11MtCO_2e. Emissions savings in industry can be achieved by targeting the large point sources such as the Grangemouth cluster. Carbon capture and storage represents a crucial technology for the decarbonisation of industry with rapid rollout needed in the 2030s. However, analysis by Child et al. (2018), indicates that using CO_2 captured from the air in power-to-gas or power-to-liquid fuel plants might present a route to de-fossilising the Scottish energy system, which might reduce reliance on CCS.

Scotland is well placed to make use of CCS or engineered removals of greenhouse gases because of its proximity to CO_2 storage sites in the North Sea.

In the near term, decarbonisation of transport will likely be centred around road transport and shipping rather than aviation because there are clearer routes to doing this. For fleet vehicles such as buses and ships, early action is needed given the long lifetimes of these vehicles which would either lock in GHG emissions or lead to stranded assets. The 2030 ban on new sales of petrol and diesel cars will increase uptake of low/zero carbon vehicles such as EVs. Others have suggested a ban on petrol and diesel vehicles in Scottish towns and cities, which could encourage shifts to other forms of transport such as public transport, walking or cycling. This would also improve air quality of urban areas by reducing particulate matter and NO_x emissions.

Land use and GHG removals

Land use and agriculture are two important sources of residual emissions in Scotland (CCC, 2020c). Current accounting in emissions inventories suggests land use, land use change and forestry (LULUCF) is a net sink of GHG emissions. However, changes to the way in which peatland emissions are accounted for and the global warming potential of methane could shift this sector from a sink to a net source of GHG (CCC, 2020a). Increased rates of afforestation or peatland restoration reduce the net source of LULUCF emissions, or even result in a net sink. Restoration of peatlands is likely to produce an immediate improvement in GHG emissions to reduce the size of the source, but it will take more time before peatlands become a net sink.

Scotland has three strengths that would help deliver GHG removals:

- High forest coverage (1.4Mha in 2018) with a target of planting 18,000ha/yr by 2025 (up from around 9,000ha/yr in 2018).
- Large land area which could be used for cultivation of bioenergy crops (analysis by Vivid suggests 0.1-0.2Mha of land freed up for this purpose (WWF, 2019)).
- Access to CO_2 storage sites in the North Sea.

In addition to natural resources, Scotland has a legacy of skills and infrastructure from the oil & gas industry that could be leveraged to help deliver CCS at scale. CCS is an important component for engineered removals in the form of direct air capture (DAC) and bioenergy with CCS (BECCS). Scotland has ambitions to deliver 5.7MtCO_2e of negative emissions by 2032 through various forms of BECCS and DAC.

It is suggested that agricultural emissions should aim to fall by 17% by 2032 and 37% by 2045 to avoid the need for steep reductions in the 2040s (WWF, 2019). A number of mitigation measures exist which target different types of GHG emissions from agriculture. Methane emissions from ruminant livestock could be reduced with food additives (although these are only effective when the animals are not grazing the land); breeding and genetic development to produce lower emitting breeds; and management of the total ruminant population. N_2O emissions can be reduced with strategies to understand crop requirements and improve application of nitrogen fertilisers. CO_2 emissions from energy use on farms can be improved with use of renewable energy and low carbon farm vehicles. Farmers and landowners may also have the opportunity to explore multifunctional land uses such as agroforestry. Emissions from agriculture are unlikely to ever reach zero but a concerted effort to reduce emissions and increase offsets through land use change is needed.

References

CCC, 2020a. Reducing emissions in Scotland progress report. CCC. London

CCC, 2020b. Letter: Lord Deben, Climate Change Committee to Roseanna Cunningham MSP. Available at: https://www.theccc.org.uk/publication/letter-lord-deben-climate-change-committee-to-roseanna-cunningham-msp/

CCC, 2020c. The Sixth Carbon Budget: The UK's path to Net Zero. CCC. London

Child, M., Ilonen, R., Vavilov, M., Kolehmainen, M. and Breyer, C., 2019. Scenarios for sustainable energy in Scotland. *Wind Energy*, *22*(5), pp.666-684.

Existing Homes Alliance, 2019. Response to Energy Efficient Scotland Consultation

NAEI, 2021. Greenhouse Gas Inventories for England, Scotland, Wales & Northern Ireland: 1990-2019. Available at: https://naei.beis.gov.uk/reports/reports?section_id=3

National Grid ESO, 2020. Future Energy Scenarios. National Grid ESO. Warwick

SPEN, 2020. SP Distribution Future Energy Scenarios. SP Energy Networks. Glasgow

WWF, 2019. Delivering on Net Zero: Next steps for Scotland. WWF Scotland. Edinburgh

Appendix II - Energy System Modelling with ESME

Model overview

ESME was originally developed to evaluate the role of innovation in UK energy system decarbonisation, from energy resources and conversion through to end use in buildings, transport and industry. It is used by ESC, Government, industry, the Climate Change Committee and academia.

ESME is an optimisation model and finds the least-cost combination of energy resources and technologies that satisfy UK energy service demands along the pathway to 2050. Constraints include emissions targets, resource availability and technology deployment rates, as well as operational factors that ensure adequate system capacity and flexibility. It is focussed on the physical components of such a system – infrastructure, energy flows and associated costs – and does not look at other layers of the system such as commercial aspects or communications between actors.

Importantly, ESME includes a multi-regional UK representation and can assess the infrastructure needed to join up resources, technologies and demands across the country. This includes transmission and distribution networks for electricity and gas, and pipelines and storage for CO_2. This feature of ESME means we have been able to evaluate decarbonisation pathways for Scotland within in the wider context of UK climate change policy. Specifically, we are able to delve into the interactions between Scotland and the rest of the UK including flows of electricity and hydrogen.

The philosophy within ESME is of modelling the UK as an energy island. This means that ESME designs do not rely on international cross-border electricity infrastructure to absorb excess generation or import electricity when indigenous sources are not available. Policy-neutrality is a fundamental principle when using scenarios built in ESME, wherein minimal second-guessing of how policy could de-risk investment in the future takes place. By adopting this principle, the energy system can be thought of as being designed centrally, and technology risk is reduced.

Limitations of the modelling

Key methodological elements

Data: ESME is a data-driven model, with projections for demands, technologies and resource being central to its decision making. These projections are, by their nature, uncertain, and results should be assessed carefully in this context. Notably, decisions made in one sector can radically affect the timing or extent of decarbonisation in others.

Linearity: Like many similar models, ESME adopts a linear representation for technology and resource costs, and for constraints affecting the energy system. Such a representation precludes "lumpy investment", where technologies are deployed in blocks of minimum size, and neglects any cost scaling of technologies. This has particular impacts on key sectors, as outlined below.

Spatial resolution: ESME is a multi-regional model, allowing the broad features of transmission and distribution of energy across the UK to be assessed. However, only limited information at finer granularity is integrated. Demand centres are not spatially positioned, and local challenges of transmitting energy within a region are not substantively modelled. Where physical limitations are key (for example, where there are permitted locations for particular power stations), these are implemented as regional constraints within the model.

Sector representations: Within ESME each current and future emission point is not modelled independently. Instead, a set of coarse archetypes is used to characterise users of energy and sources of emissions across the whole system. In each case, sector representations are chosen to retain as much operational flexibility as possible, ensuring that innovations in technology properties and control do not impose overly constraining routes. Key examples of these representations are:

- **Heating in buildings**: A small set of building archetypes is used to represent the UK's complex building stock. Within this framework, a simplified methodology is employed where heating supply and demand are pooled and subsequently balanced. This weakens the link between specific building types and heating systems; at single building level not all possible system combinations can be distinguished. The retained flexibility within ESME permits multiple plausible operational interpretations for heating systems – in particular, the operation of gas/hydrogen-fired and heat pump systems across different times of day and seasons regularly hints at hybrid heat pumps as a solution likely to be valuable to the energy system. It should be noted that the heating system costs remain subject to the linearity requirement described above, meaning that there are no additionality effects or cost savings implied for installation of hybrid systems of any type.
- **Industry**: Archetyping of industry in ESME is informed by fuel consumption data provided regularly by BEIS. These data provide a natural disaggregation of industrial fuel use into sectors and end-uses. Within ESME, a set of industrial interventions is available that allows these sectors to transition to low or zero-carbon. As noted above, ESME does not attempt to spatially locate industrial sites within a region and to consider the local infrastructure needs consistent with decarbonisation. Crucially, any retained energy flows within industry must be reconciled with the infrastructure available in the future.
- **Energy network infrastructure**: All of the key networked energy carriers – notably electricity, gas and hydrogen – are subject to archetyping within ESME, representing energy at particular voltage or pressure levels. At the transmission level, it is assumed that all barriers to network reinforcement can be overcome with sufficient network investment. For future distribution of low-pressure hydrogen, ESME assumes that local networks can be generated only through repurposing of existing gas distribution networks at a fixed, linear repurposing cost. Network operation and maintenance costs are also assumed to be linear, meaning that additional costs associated with more infrequent flows of gas through the networks are not captured fully.
- **Non-energy system sectors**: ESME is first and foremost an energy systems model. This means it constructs energy systems by making choices about technologies that satisfy energy demands (power, heating, transport, industry and infrastructure). The major GHG emitted by the energy system is CO_2. However, Scotland's (and the UK's) net zero GHG target mean that it is insufficient to consider only the energy system and only CO_2. Non-energy system sectors (land use, agriculture, waste management) need to be accounted for in the modelling. These sectors are associated more with non-CO_2 GHG emissions (methane (CH_4), and nitrous oxide (N_2O)). However, ESME does not currently have the functionality to make in-model decisions about strategies/methods to reduce such emissions from these sectors. Therefore, in order to account for them, emissions trajectories for these sectors are determined off-model and introduced as exogenous assumptions in ESME. Emissions trajectories for these sectors are generally taken from work conducted by other organisations (e.g. CCC). These trajectories represent hard-coded emissions that ESME must allow for but is unable to directly influence (through suitable technology choices). Instead, ESME must make decisions in the energy system to ensure that non-energy system emissions are accounted for.

Hybrid heating systems

Given the important role of hybrid heat-pump/hydrogen boiler systems in keeping homes connected to the gas distribution network in the modelled scenarios, it is important to understand that there is uncertainty around the level of hybrid systems.

ESME distinguishes between a number of building types with different built form and thermal performance, but it does not distinguish buildings on the basis of their local infrastructure (e.g., how much headroom is in the local electricity grid).

Within a given spatial node in ESME (for example, Scotland) every space heating generating technology contributes to a general “pool” of space heat which can be used to meet demand for space heat of any building of any type. In a very simple scenario with two homes with identical heat demands and two heat technologies – heat pump and hydrogen boiler – ESME may well find it cheaper to meet their combined demand by building a heat pump of capacity C which is operated near its capacity most of the time (high load-factor), and a hydrogen boiler of capacity C which does little except at times of peak demand (low load-factor, than it would to build a heat pump of capacity C which is run to meet the demand of one home, and a hydrogen boiler of capacity C which is run to meet the demand of the other home.

From ESME’s point of view, the capital costs of installing the heating systems and any necessary changes to infrastructure would be the same in both situations, but the operational cost would be lower in the first situation (for certain relative fuel costs, at least). Although all space heat is pooled, the first situation can only be interpreted as two hybrid systems, because the heat production profile of either technology *by itself* would not match the heat demand profile of a single home.

If, in a more realistic model of this simple scenario, existing infrastructure supplying the homes was such that the hybrid system avoided the need for reinforcement by cutting peak demand for electricity, say, then it may also beat the non-hybrid system on capital costs. But it could also be the case that the hybrid configuration is more expensive overall: For example, if one home is actually not on the gas grid, then the hybrid configuration would mean connecting it, which may more than cancel the savings in operational costs. It could also be that both homes have a connection to gas grid, but that installing a hybrid in one home (home ‘A’) is enough to trigger an expensive reinforcement of the electricity network that supplies it, while installing a dedicated heat pump in the other home (‘B’) would not require any grid reinforcement. In this case, a setup with a hydrogen boiler at A and heat-pump at B could again be cheaper than the hybrid setup, despite the higher operational costs. It may simply be that the additional capital costs of the hybrid systems vs two standalones outweigh the operational savings.

Using ESME to develop scenarios for Scotland

The scenarios modelled in this analysis are broadly characterised by adjustments to technology, land-use assumptions and energy service demands. Adjusting these three elements places the scenarios in different points on the scenario framework described in section Figure 2.1.

In ESME, end use energy service demands (such as annual car passenger-kilometres or building indoor temperatures) as well as land use assumptions (such as annual carbon sequestration from forestry or peatlands) are ‘inelastic’, i.e. they are fixed, **exogenous** assumptions. When we refer to a land use or demand adjustment, this is made off-model and necessarily features in the scenario. Land use and demand adjustments are categorised as societal change in the scenario framework Figure 2.1).

By contrast, technologies are a set of options, the selection of which is part of the endogenous optimisation taking place within the model. Here we must distinguish between two types of technology adjustment:

- **Technology additions**: In some cases, we are proposing adding a new technology to the option set (e.g. direct air capture facilities and higher quantities of biomass). This has the effect of expanding the solution space. These all contribute to ESME's ability to achieve GHG targets in the TEC quadrant, relative to Standard ESME.
- **Technology deployment**: In other cases, we will propose a deployment constraint for an existing technology (e.g. a minimum capacity of offshore wind in 2030 aligned with the non-statutory target). This has the effect of reducing the solution space the model can explore, by prohibiting all pathways that fall below a minimum – or exceed a maximum – capacity for that technology.

Technology adjustments are categorised as technology innovation in the scenario framework (Figure 2.1).

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