Sensitivity Analysis of Net Zero Pathways for UK Industry

UKERC Working Paper

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Introduction to UKERC

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Contents

1. Executive summary

The Net-Zero Industry Pathways (N-ZIP) model, developed by Element Energy, has been used by both the Climate Change Committee (CCC) and the Government to explore how industry can be decarbonised in way that is consistent with the UK's net-zero greenhouse gas (GHG) target. The model includes information on carbon prices, fuel and technology options, and the projected future deployment of hydrogen and CO_2 infrastructure. The model then combines this information to produce a decarbonisation pathway for industry to 2050, with outputs including the level of emissions in each year and the technologies and fuels being used.

The characteristics of the resulting pathways are dependent on these assumptions. Element Energy, the CCC and the Department for Business, Energy and Industrial Strategy (BEIS) have undertaken some sensitivity analysis to explore how changes in key assumptions affect the results. However, given the importance of the model in informing policy on industrial decarbonisation, in this working paper we undertake further analysis to explore how the model results are affected by changing a wider range of inputs than previously studied.

The aspects explored are the:

- extent to which resource efficiency is applied;
- discount rate used to compare the net present value (NPV) of options;
- carbon cost trajectory that is assumed;
- cost and availability of CO_2 transport and storage infrastructure;
- cost of fuels;
- cost and availability of hydrogen; and
- constraints applied to fuel supply, supply chains, and CO_2 injection rate.

We find that the model results are generally robust to relatively wide variations in the input assumptions that we have explored. However, a number of areas are highlighted for further analysis. At the moment assumptions about resource efficiency and energy efficiency are exogenous to the model. Further work is needed to explore the trade-off between these measures, which reduce the demand for energy by industry, and the technology and fuel options in the model that reduce the carbon intensity of the energy that is used. The model results also highlight the critical importance of carbon capture and storage (CCS) to industrial decarbonisation, even when transport and storage costs are high. Further work is needed to validate this result, including making sure that the model incorporates the full range of competing abatement options that might be viable alternatives to CCS (especially for sites that are not part of large industrial clusters).

2. Introduction

Industrial products are essential for daily life and a vibrant economy. They include a wide variety of goods from vehicles, to food and COVID-19 vaccines. However, the global industrial sector accounts for one-quarter of total primary energy demand in 2019 (IEA, 2020). More than 70% of that demand is met using fossil fuels, making the industrial sector responsible for 25% of global CO_2 emissions (IEA, 2020). Although challenging, it is vital to reduce industrial sector emissions to avert dangerous climate change.

The UK government has published an Industrial Decarbonisation Strategy that aims to reduce industrial sector emissions – which represent 16% of the total UK emissions[1] – by two-thirds in 2035 and by 90% by 2050 (UK Government, 2021). The strategy aims to use carbon pricing mechanisms, fund large infrastructure projects, encourage low-carbon fuel switching, and help improve energy efficiency for industrial sites. Industrial sector modelling plays a major role in informing government policies, developing net-zero industrial pathways, and analysing the deployment of new technologies and infrastructure.

The Net-Zero Industrial Pathways (N-ZIP) model[2] was developed by Element Energy (Element Energy, 2020) and used to inform the sixth carbon budget advice from the CCC (Climate Change Committee, 2020) and the Government's Industrial Decarbonisation Strategy by modelling alternative pathways for deep-decarbonisation across UK industry. In contrast to economy-wide optimisation models that focus on decarbonising energy supply, N-ZIP provides detailed analysis of the industrial activities that drive demand for energy and cause greenhouse gas (GHG) emissions. N-ZIP is a spatially disaggregated, bottom-up model that estimates the economic value of different options to decarbonise industrial processes across UK industrial sites. The model then uses these results, alongside site and economy-wide constraints, to produce the final decarbonisation pathway based on a least-cost approach. The resulting N-ZIP pathways are possible routes for substantial industrial decarbonisation by 2050 for a given set of parameter assumptions.

The characteristics of the resulting pathways are affected by these assumptions. Element Energy have explored some of these sensitivities focusing on some assumptions for which there is uncertainty over which real-world conditions will prevail. These sensitivities have included altering the assumptions for the "optimism bias" parameter relating to fuel switching technologies, the cost of electrical connections, the development of "secondary" industrial clusters, the extent of key supply-chain constraints, and changes to some fuel prices. However, given the significance of the results, further analysis is warranted. The sensitivity analysis completed in support of

[1] According to the Department for Business, Energy and Industrial Strategy (BEIS) classification of the sector, emissions from UK industry were 72 $MtCO_2e$ in 2018, which is 16% of total UK emissions in that year. The N-ZIP model includes additional sectors, such as offshore oil and gas terminals and non-road mobile machinery, resulting in emissions of 110 $MtCO_2e$ in 2018.
[2] The model is open-access and can be downloaded free from the CCC website.

the CCC and Government reports could only consider a limited number of additional runs for each assumption examined. Additionally, there is a far wider set of parameters that will affect the results to a greater or lesser extent, e.g. the cost of carbon. It is also instructive to consider how the model responds to much greater changes in some parameters (e.g. costs) in order to evaluate its stability and the effect that other changes might cause.

To address these issues this paper explores how a range of alternative values for some key N-ZIP model parameters impact the model results, including the pace and extent of decarbonisation over the period to 2050, the technologies and fuels used, and the costs involved.

The rest of this paper is organised as follows: Section 3 briefly introduces the model structure and some representative results based on parameters that match the 'Balanced' scenario from the CCC's sixth carbon budget advice (Climate Change Committee, 2020). Section 4 then compares the equivalent results produced by the model when selected key assumptions are varied. The aspects explored are the:

- extent to which resource efficiency reduces demand for industrial products;
- discount rate used to compare the net present value (NPV) of decarbonisation options;
- carbon cost trajectory that is assumed;
- cost and availability of CO_2 transport and storage infrastructure;
- cost of different fuels;
- cost and availability of hydrogen; and
- constraints applied to fuel supplies, supply chains, and CO_2 injection rates.

Section 5 provides an alternative disaggregation of the results in order to highlight the role of high and low-temperature heat provision, a key challenge for industrial decarbonisation. Finally, Section 6 provides conclusions and some suggestions for future work.

3. Modelling the UK industrial sector

The N-ZIP model disaggregates UK industry into 28 sectors. It includes 1277 location-specific industrial sites with each site having a set of defined industrial processes, leading to a total of 6281 site processes in the model.

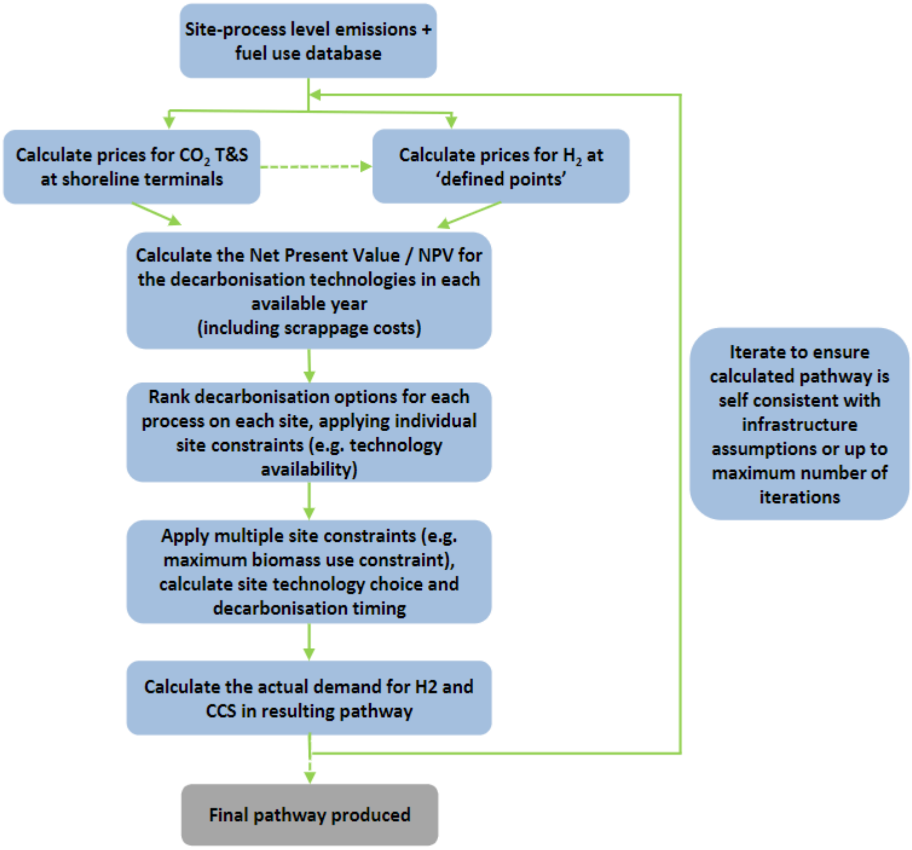
The N-ZIP model working flowchart is shown in Figure 1. For each industrial site, the most appropriate hydrogen production and CO_2 transmission and storage terminals are assigned based on the distance of the site to those terminals. Emissions and fuel use databases are created for each site-process combination. This includes both baseline and resource efficiency and energy efficiency (REEE) emissions projections. Then, based on the site location, the decarbonisation infrastructure cost is calculated considering that dispersed sites[3] incur greater costs for hydrogen and CO_2 transport. The model then determines the NPV of the decarbonisation options for each process and ranks them, while also taking account of individual site and infrastructure constraints, and implements those that are cost-effective at the assumed carbon price. The final step is to ensure the pathway is consistent with economy-wide constraints relating to biomass availability, supply chain limitations, hydrogen production and carbon capture and storage (CCS) demand.

Some parameters are defined exogenously and used as inputs to the N-ZIP model. These are described in full by Element Energy (Element Energy, 2020) and include:

- "Baseline" energy and emissions projections to 2050, using estimates from the CCC that draw on historical data on energy (from the Digest of UK Energy Statistics), greenhouse gas emissions (from the National Atmospheric Emissions Inventory) and energy and emissions projections produced by BEIS.
- Assumptions about the level of "resource efficiency and energy efficiency" (REEE) that will occur over time are based on Scott et al. (2019). This paper provides emission reductions from the baseline and are used as an input to N-ZIP.
- The capacity and location of hydrogen and CO_2 transmission and storage (T&S) infrastructure that becomes available to industry over time.
- The cost, suitability, and performance parameters of alternative technologies.
- Constraints on other resources, such as that which results from the competition for bioenergy with non-industrial applications, which are not endogenised in N-ZIP.

[3] The model distinguishes between industrial sites that are part of a "cluster" and dispersed sites, which are those located more than 25 km from a cluster.

Figure 1: N-ZIP model flowchart (Element Energy, 2021)

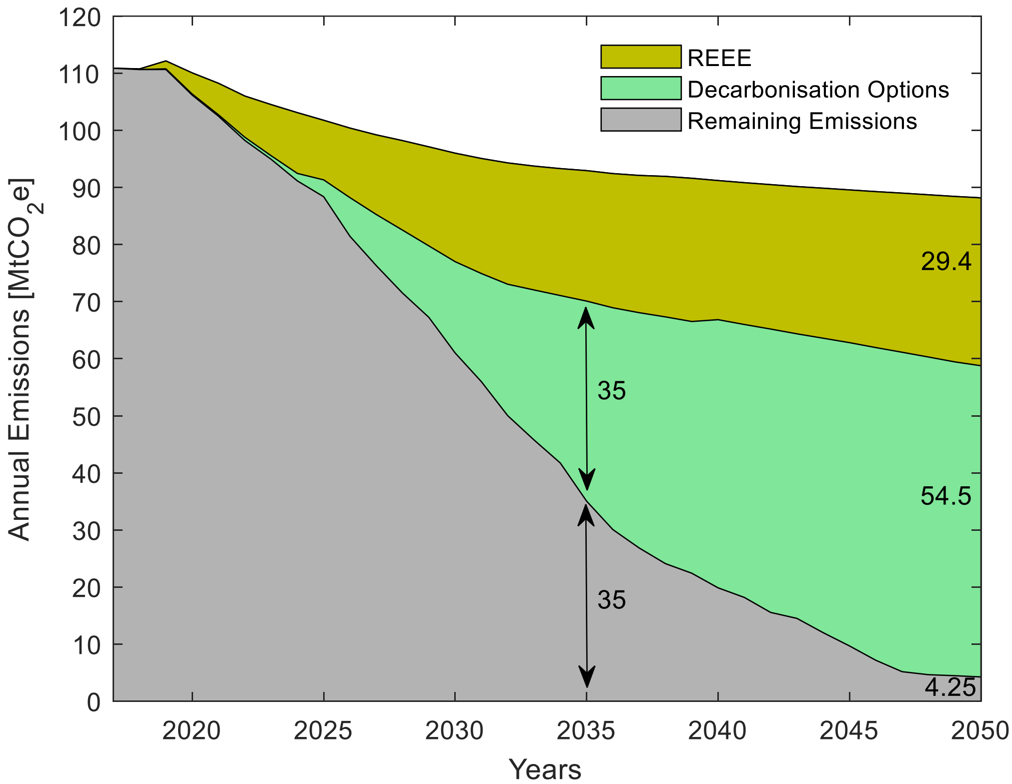


The CCC defined five economy-wide scenarios for the UK economy to reach net zero by 2050 (Climate Change Committee, 2020). The narrative of these scenarios was reflected in five main net-zero industrial pathways simulated by N-ZIP[4]. The 'Balanced' scenario is the main pathway considered, which prioritises low-regret measures and implements a balanced mix of decarbonisation technologies in the long-term.

The emissions abatement for the CCC Balanced scenario can be replicated using the latest version of the N-ZIP model, and is shown in Figure 2. After decarbonisation options are applied by N-ZIP, industrial emissions decrease by 96% by 2050 to reach 4.3 $MtCO_2e$ compared to 110.8 $MtCO_2e$ in 2017. The decarbonisation options and REEE contribute emissions reductions in 2050 of 54.5 $MtCO_2e$ and 29.4 $MtCO_2e$ respectively, compared to the baseline projection in that year. The value of avoided/abated carbon emissions is a key driver underpinning this abatement level; the high carbon value (which rises from £104/tCO_2 in 2020 to £346/tCO_2 in 2050) makes it more cost-effective to switch to low-carbon options than keep with existing technologies and fuels.

[4] The five pathways are; Balanced, Headwinds, Widespread Engagement, Widespread Innovation, and Tailwinds. While we consider the 'Balanced' scenario in this paper as the main pathway for the purpose of comparison, the other scenarios may result in different abatement technology choices such as the use of green versus blue hydrogen.

Figure 2: Emissions abatement for the 'Balanced' scenario.



The emissions abatement technologies for the Balanced scenario are shown in Figure 3. CCS is the single most important abatement technology in 2050, contributing an emissions reduction of 19.15 $MtCO_2e$. CCS is vital to reduce the emissions in the waste processing sector and is central to the use of blue hydrogen[5]. The combination of electrification and blue hydrogen technologies is expected to achieve approximately the same level (29.8 $MtCO_2e$) of emissions reduction as REEE measures by 2050.

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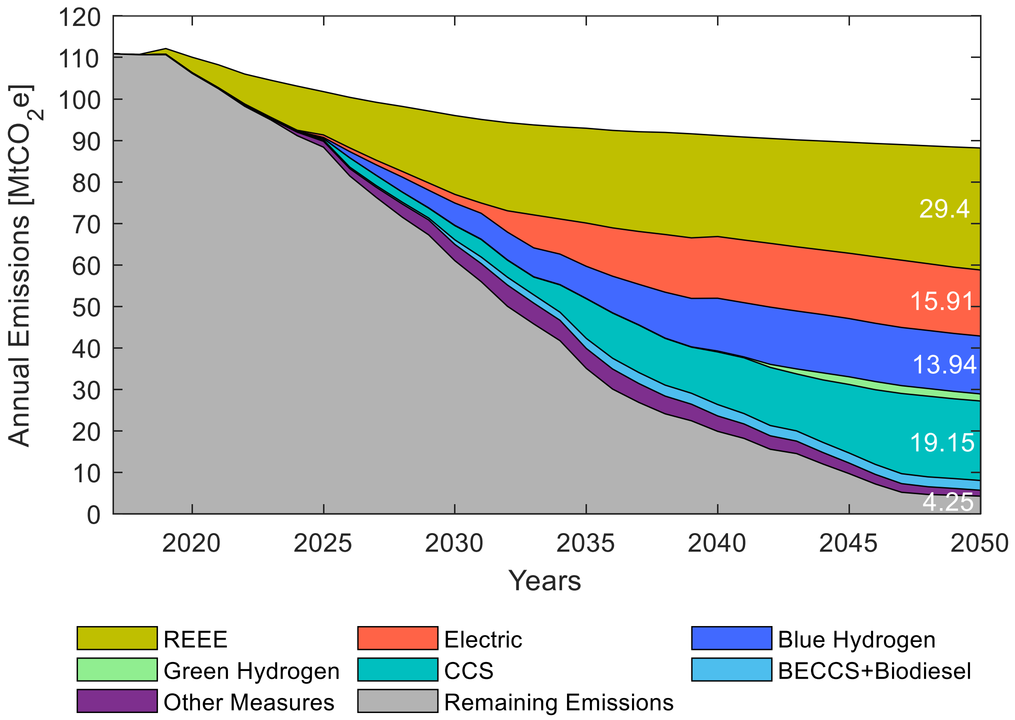
[5] Blue hydrogen is hydrogen produced through methane reforming with carbon capture.

Figure 3: Emissions abatement by technology for the 'Balanced' scenario.



The annualised net cost (total abatement measure cost, minus baseline cost) for the Balanced scenario is shown in Figure 4. The cost increases to £2.2 bn/yr in 2030 and then rapidly rises as the decarbonisation pace increases, reaching £10.5 bn/yr by 2050.

The fuel consumption for all industrial sectors is shown in Figure 5. As the level of decarbonisation increases, natural gas and petroleum use is vastly reduced. Natural gas use is predicted to decrease from 284 TWh/yr in 2020 to 33 TWh/yr in 2050. This is accompanied by an increase in the use of electricity and hydrogen, which reach 130 TWh/yr and 84 TWh/yr respectively.

Figure 4: Annual abatement measures net cost

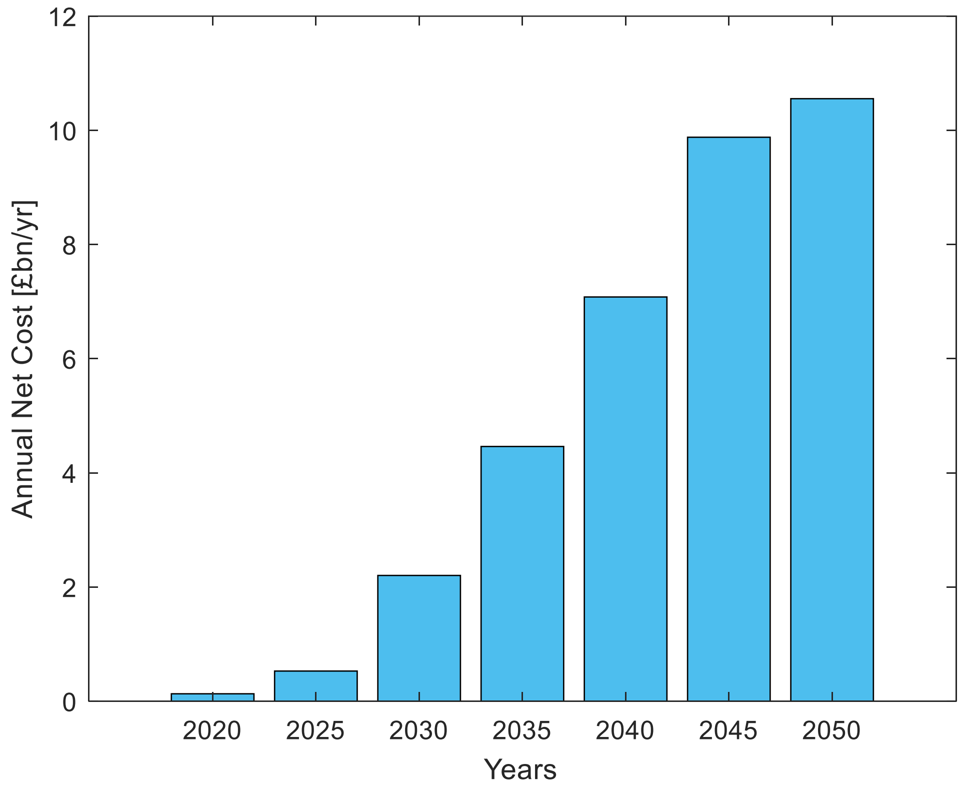
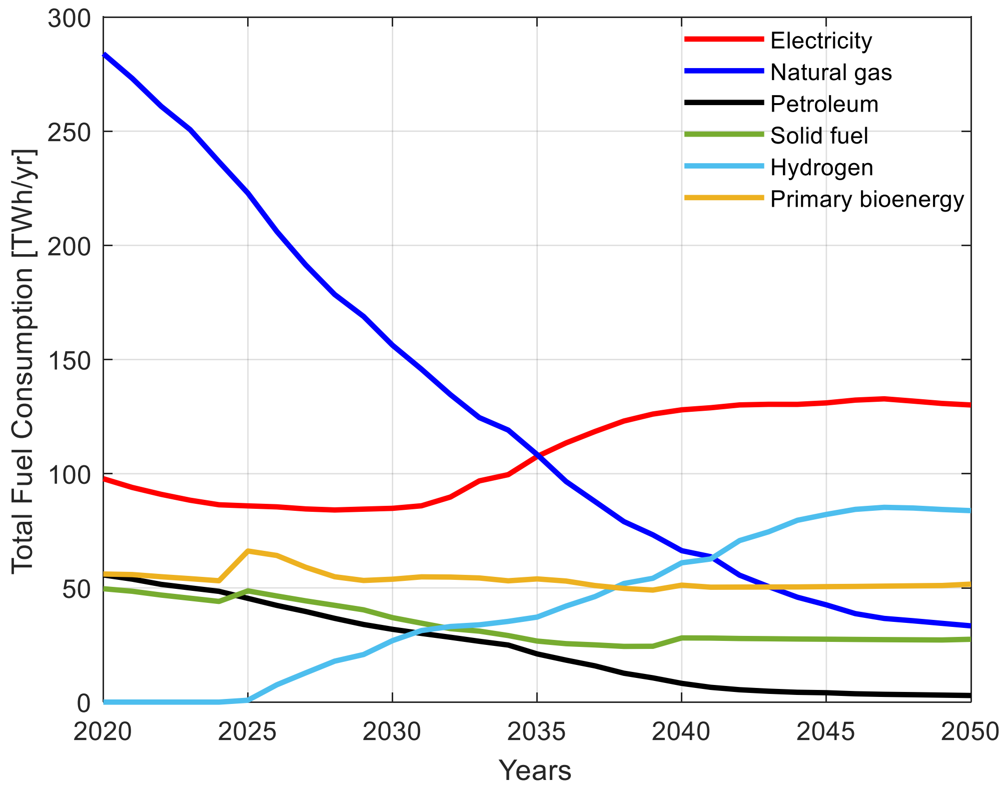


Figure 5: Fuel consumption for all industrial sectors – Balanced scenario



4. Sensitivity analysis

In this section, we explore the effect of varying several key input parameters within the N-ZIP model in order to investigate the sensitivity of its output results to these variations. In each case, the parameters other than those being explored were kept consistent with the 'Balanced' scenario, introduced in Section 3. More details about the results are given in Appendix A.

4.1 Resource efficiency

We first consider the effect of changing the level of resource efficiency (RE)[6] that is used with N-ZIP. RE relates to approaches that reduce the resources (materials and products) that industrial processes require to deliver a given output. As such, RE can reduce the upstream supply-chain activities that these processes drive and thereby reduce the emissions associated with them. Within N-ZIP, RE is modelled exogenously based on a study by Scott et al. (2019) and are applied as a set of factors that decrease the emissions and fuel use within each industrial sector progressively over time. The default N-ZIP results combine the effect of RE with additional factors relating to Energy Efficiency (EE) to give the "REEE" emissions savings. Figure 6 shows the effect that varying the level of RE has on the emissions abated by the combined "REEE" category as modelled by N-ZIP.

As RE affects the activity within each industrial sector, the impact of varying it, is equivalent to varying the baseline level of emissions that need to be abated by the decarbonisation options. That is, assessing the effect of varying the level of RE will also provide some indication of the model's sensitivity to variations in overall industrial activity (that might be caused, for example, by changes in the assumptions around the level of economic growth that underpins the baseline emissions projections).

Note that the REEE measures used in the Balanced scenario and elsewhere include some energy efficiency and other switching approaches in addition to RE. Therefore, the effect of the variations considered here is not as great as it would be if they affected the whole of the emissions decrease due to REEE. For example, in the "Resource Efficiency 50%" option in Figure 6, halving RE has far less effect than halving the difference between the original baseline and the Balanced scenario.

Figure 7 shows the effects of RE on the GHG emissions considering all abatement measures. Varying the level of RE does not have a large impact on the overall decarbonisation pathway. It mostly affects the pace of decarbonisation from 2025 until around 2035. A higher assumption about the level of RE results in a faster

[6] Note that our sensitivity choices for RE are illustrative and do not necessarily indicate likely future trends for this assumption.

decarbonisation pace. So for example, the RE 150% scenario delivers emissions abatement of nearly 10 $MtCO_2e$ more in 2030 than the RE 0% scenario.

Figure 8 explores how different RE levels affects the relative choice of abatement technologies. While increasing the level of RE decreases the remaining abatement that is required, the share of emissions reductions from the different abatement technologies remains broadly constant.

Figure 6: Effect of resource efficiency on GHG emissions abated by REEE measures only

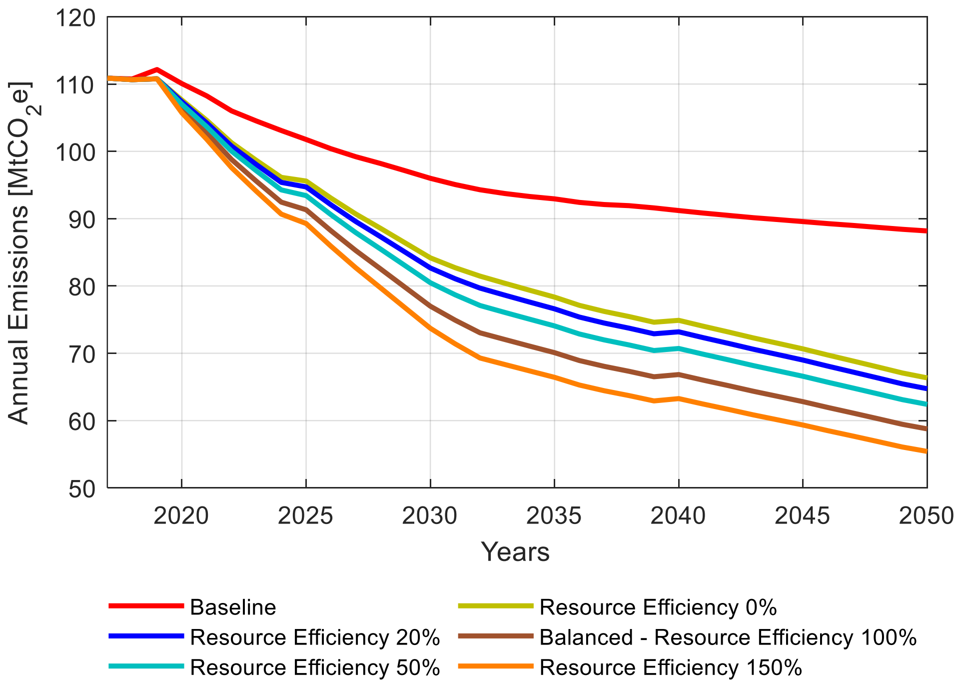


Figure 7 Effect of resource efficiency on GHG emissions considering all abatement measures

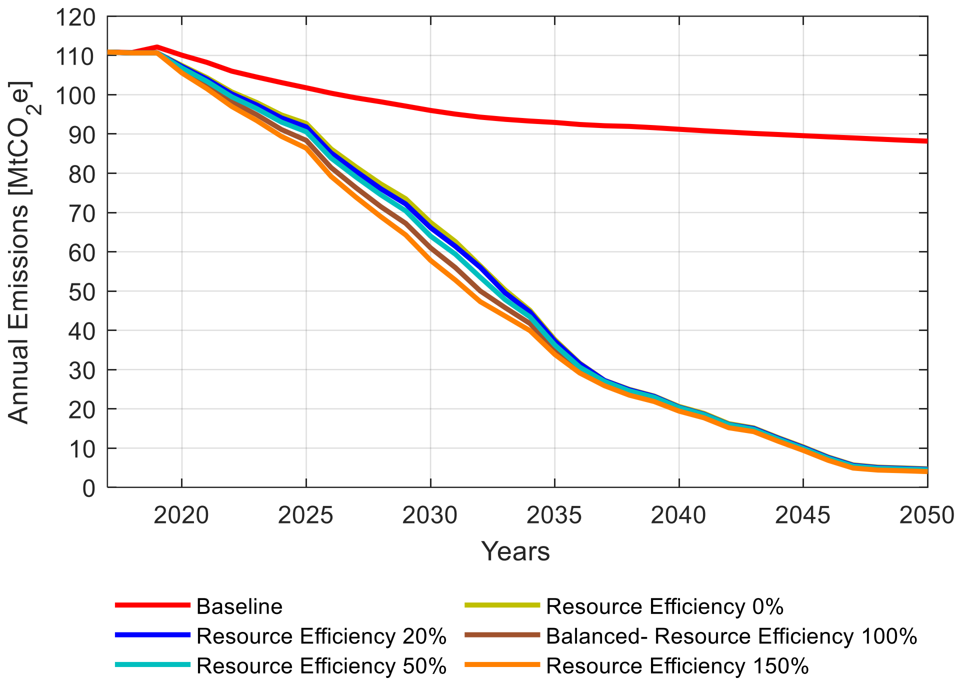
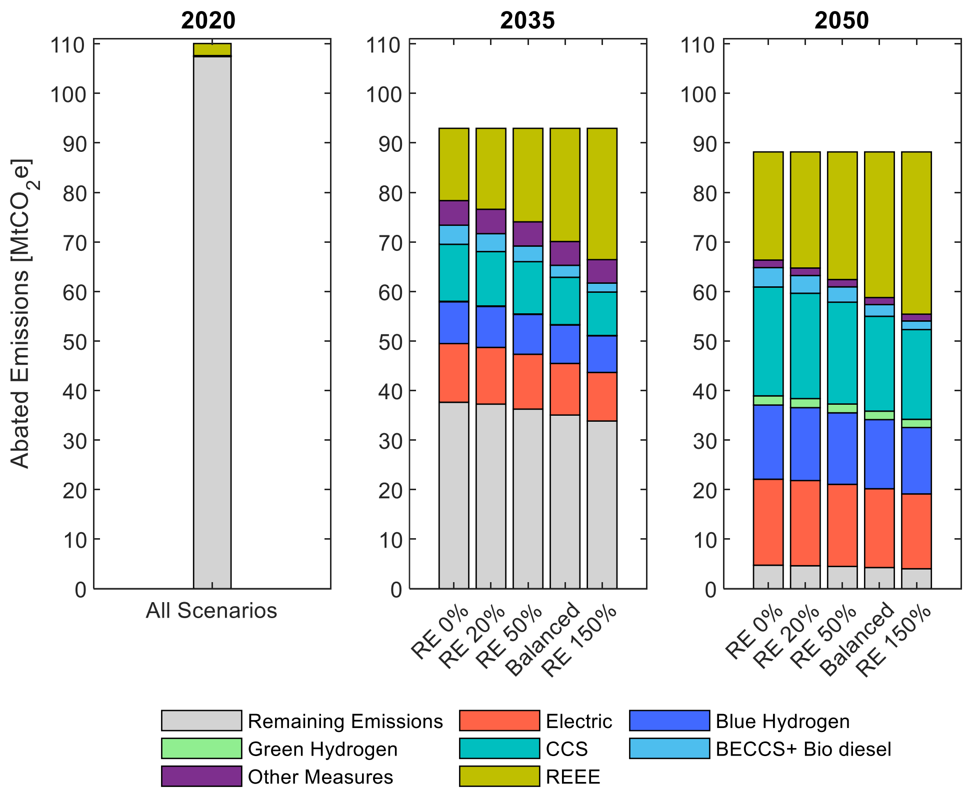


Figure 8: Effect of RE on abatement technology selection for selected years



As we might expect, this pattern continues with a (mostly) proportional effect on the net cost (Figure 9) and mix of fuels used (Figure 10). Net costs and fuel use both decrease when RE reduces the requirement for additional decarbonisation, and vice versa.

It is possible that a much greater variation in the level of industrial activity (perhaps driven by more fundamental economic changes than those due to RE) would affect some of the technology choices. For example, much lower industrial activity might influence the viability of hydrogen or CO_2 pipeline infrastructure. However, it seems unlikely that these effects will occur purely through the types of RE conventionally modelled. The effect of more directly changing hydrogen and CO_2 pipeline viability is explored later in this paper.

Figure 9: Effect of RE on net cost

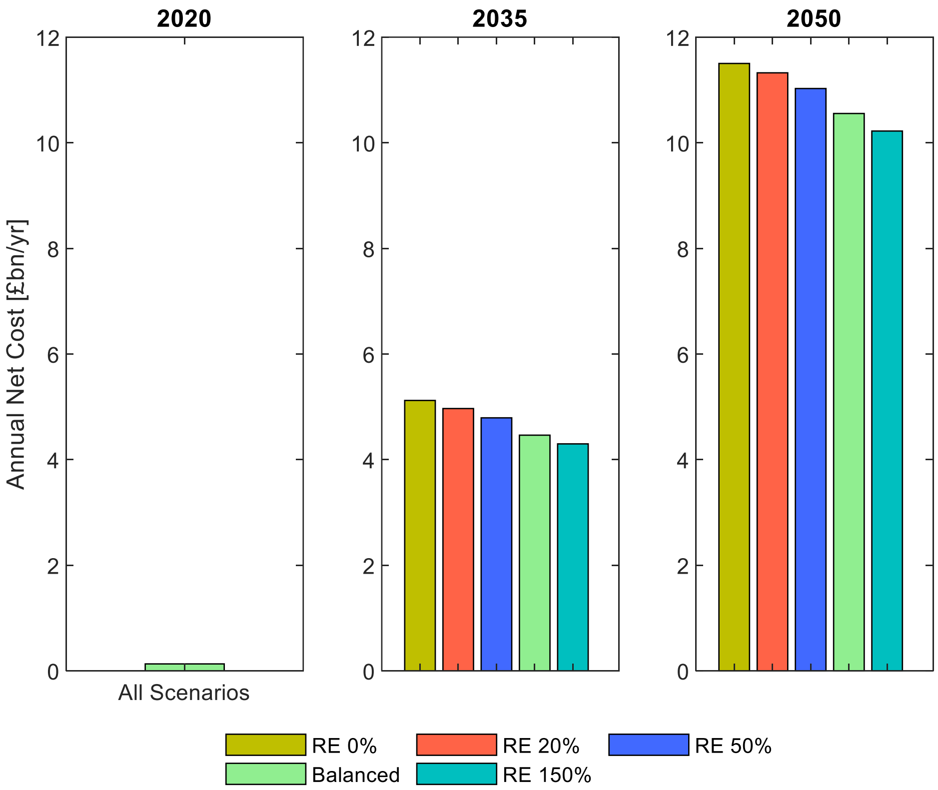
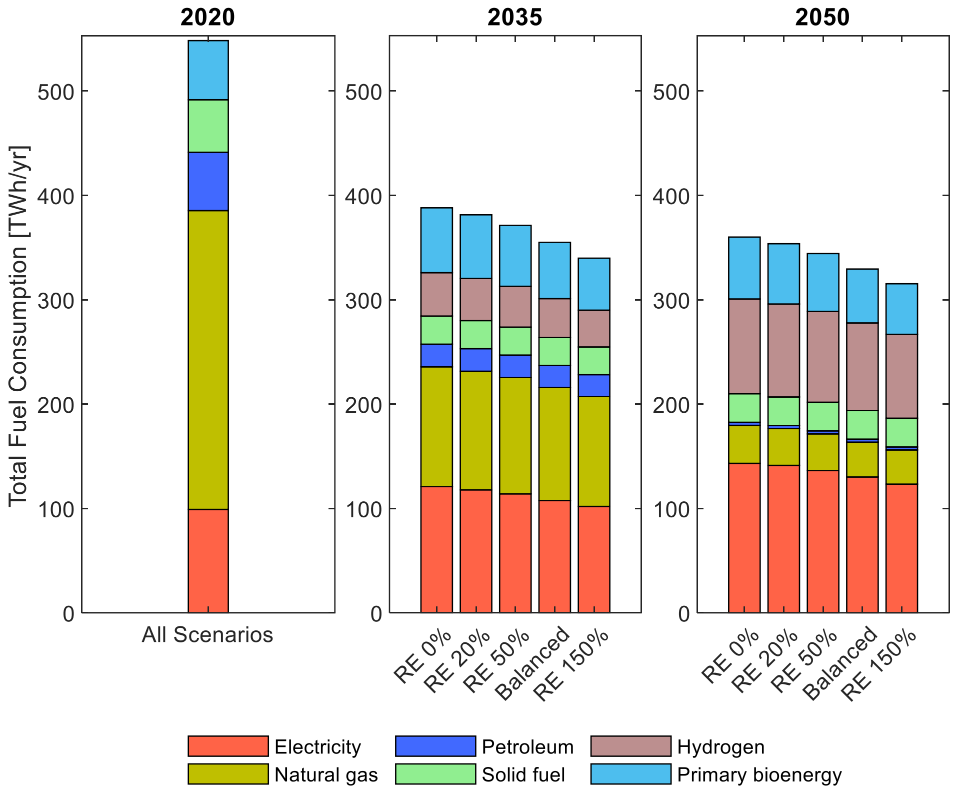


Figure 10: Effect of RE on fuel consumption



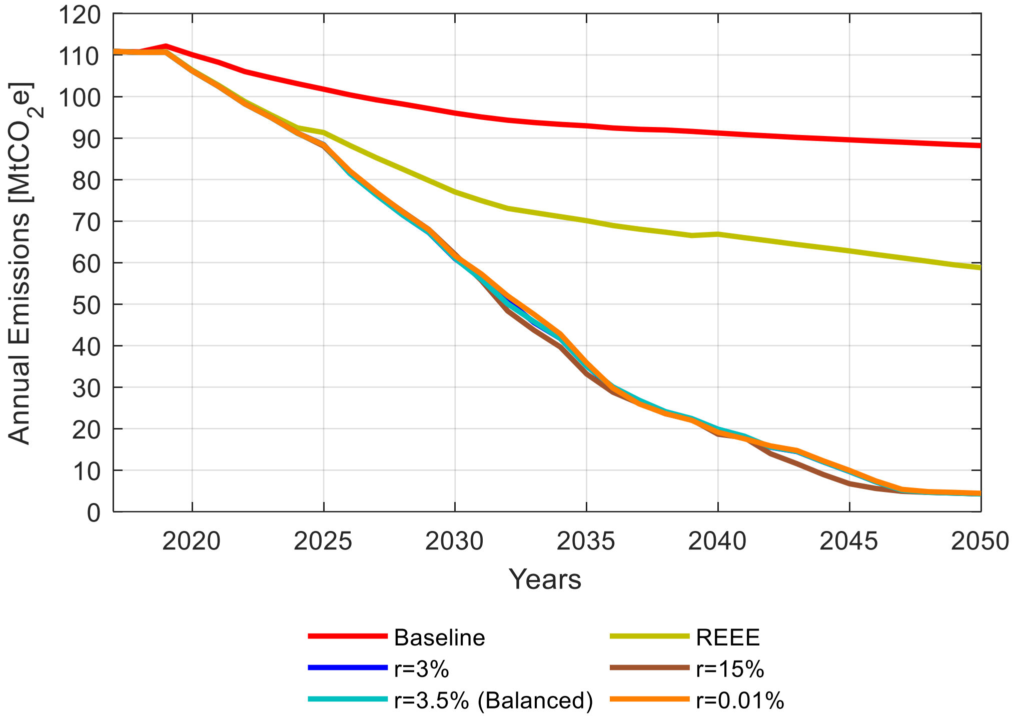
4.2 Discount rate

In this subsection, we look at the effect of varying the discount rate used in N-ZIP to perform NPV calculations[7]. Subject to constraints, these NPV calculations determine the choice of technology used to abate each emissions source. The Balanced scenario takes the Green Book discount rate of 3.5%, consistent with a societal perspective. A higher discount rate implies a lower valuation (greater discounting) of future costs, while a lower rate implies a higher valuation of future costs.

Figure 11 illustrates that even relatively large changes in the discount rate have a small overall effect on the modelled pathway emissions.

[7] The discount rates explored here do not affect the capital expenditure (CAPEX) calculation for the abatement technologies used in the model as they are already annualised.

Figure 11: Effect of discount rate on GHG emissions



However, Figure 12 shows that there are some effects on how the modelled pathway is achieved. A higher discount rate (15%) results in a slight shift away from electric and bio-based technologies towards blue hydrogen in 2050. This shift also appears to be responsible for bringing forwards the use of CCS (which sees an increase in 2035 relative to lower discount rate scenarios). These slight variations are reflected in a corresponding shift in the fuel consumption mix (Figure 14), and in net costs being brought forward (Figure 13).

Figure 12: Effect of discount rate on abatement technology selection

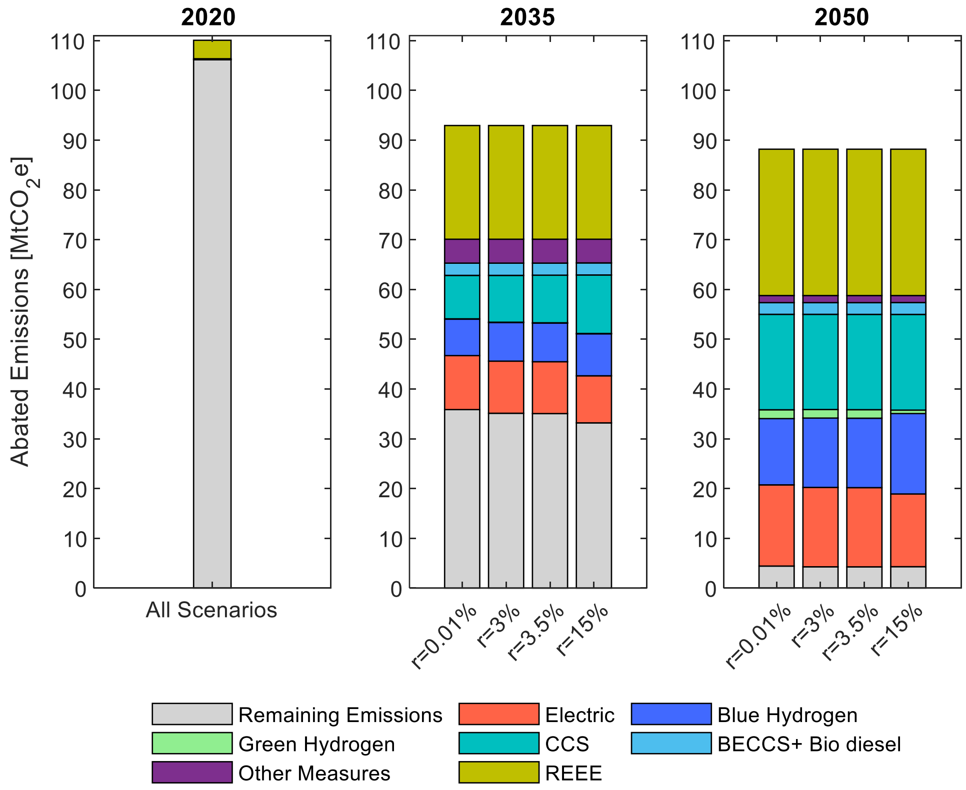


Figure 13: Effect of discount rate on net cost

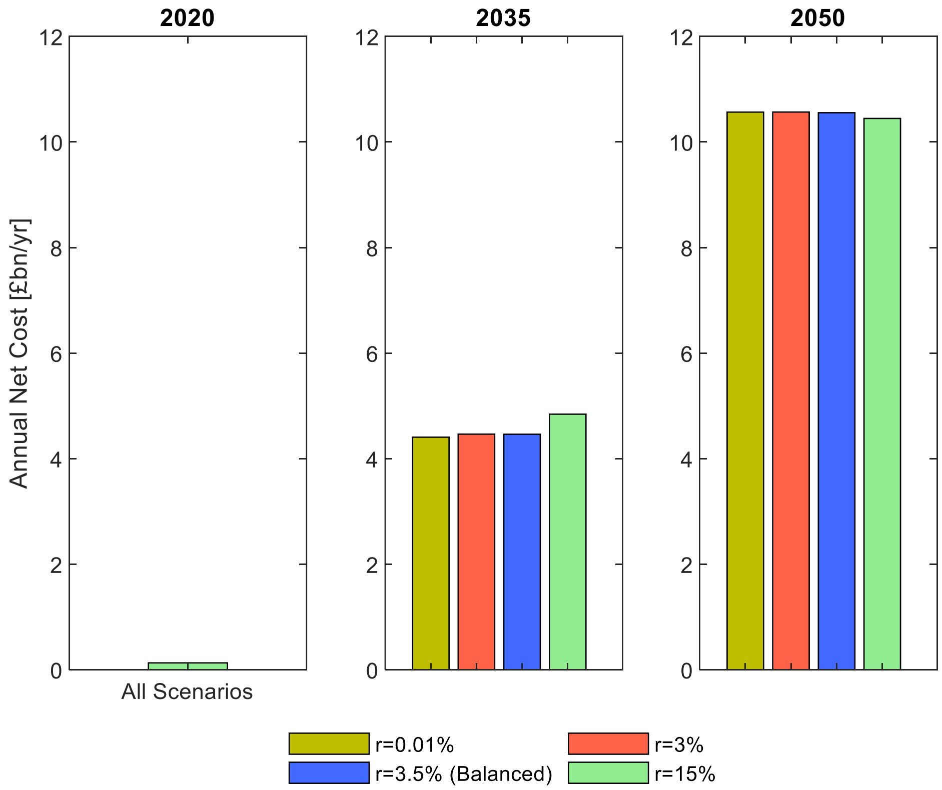
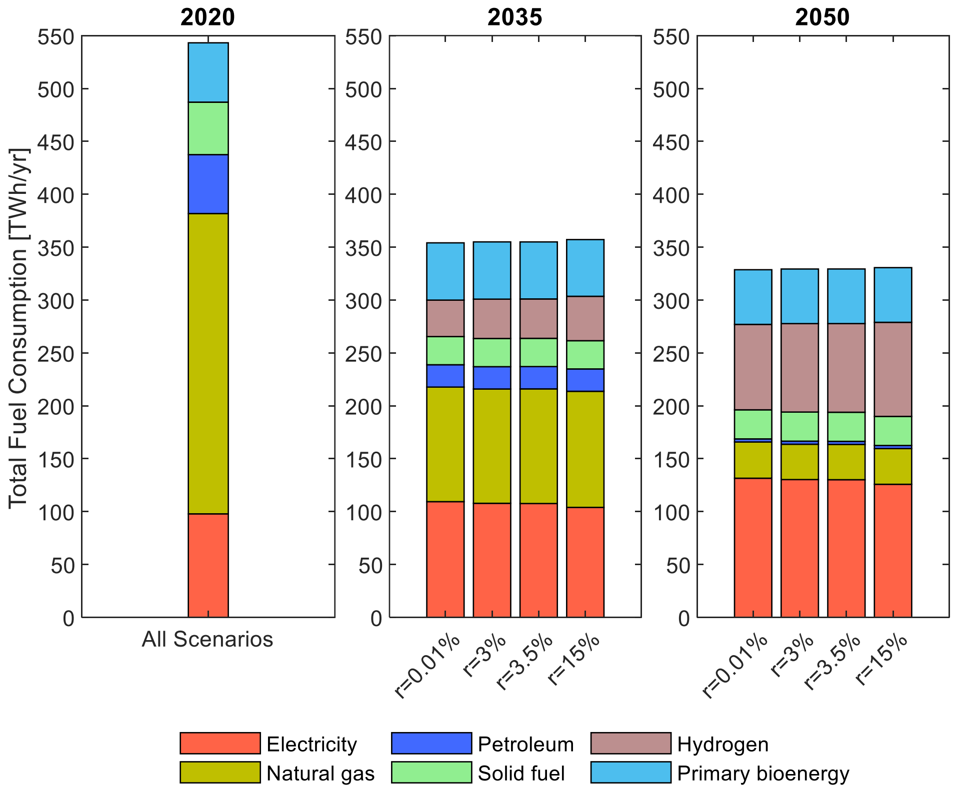
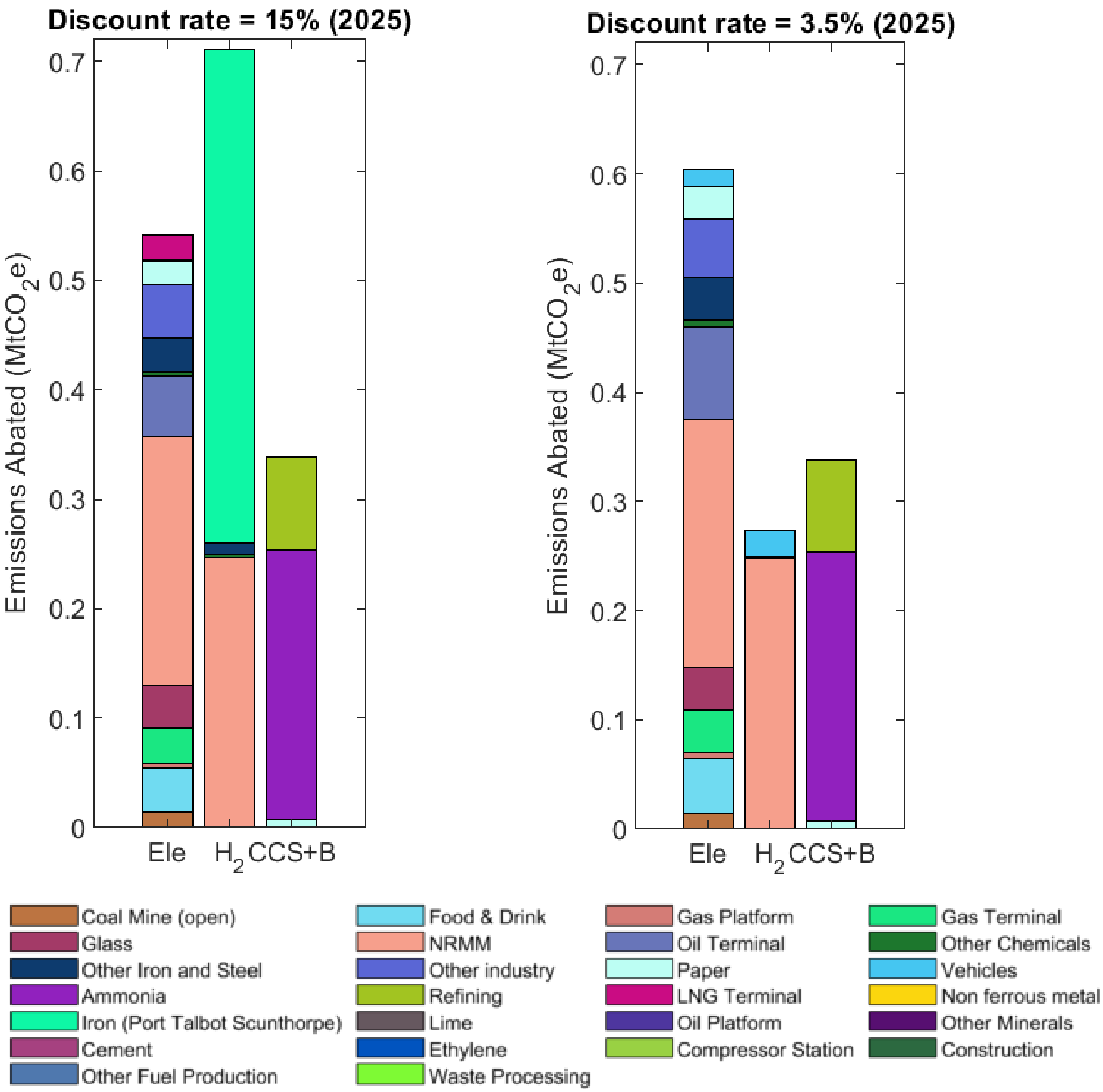


Figure 14: Effect of discount rate on fuel consumption



These aggregated results appear largely consistent between scenarios with different discount rates. However, these overall results mask sectoral level effects when a variation in discount rate may have a significant impact on when the N-ZIP model applies an abatement measure. This is illustrated in Figure 15. Here it can be seen that the application of hydrogen to the Iron industry is modelled to occur sooner (in 2025) when a higher discount rate (15% vs 3.5%) is applied.

Figure 15: Effect of discount rate on sectoral abatement in 2025

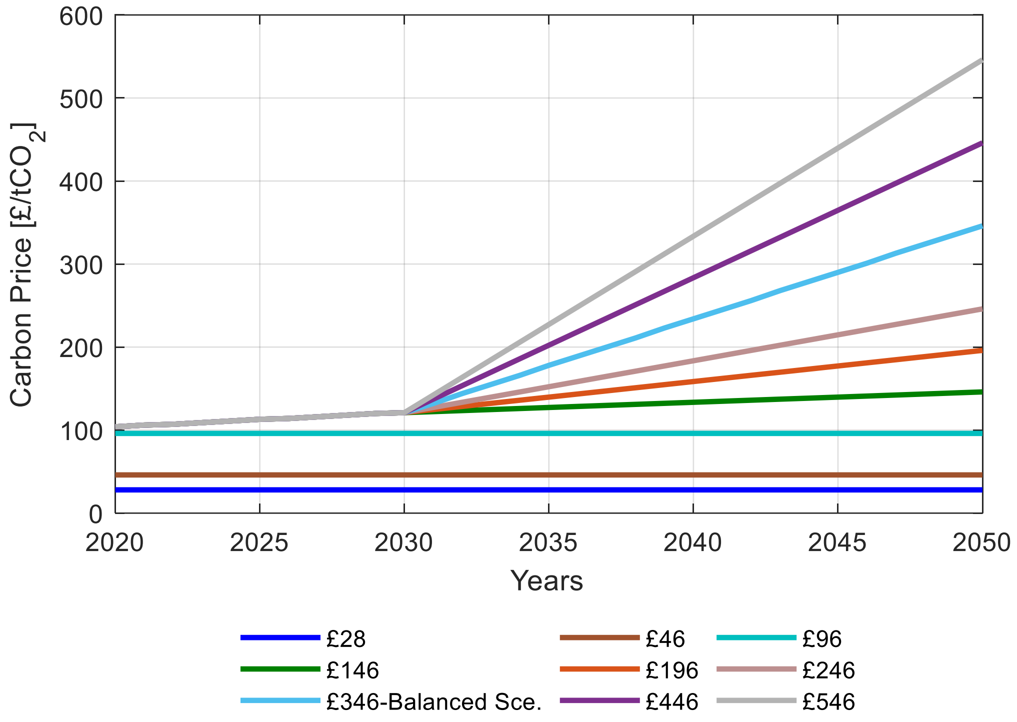


4.3 Carbon price

The next assumption varied is the carbon price. As noted in section 4.2, the carbon price (i.e. the assumed cost of emitting a tonne of CO_2) is included within the NPV calculations and so has a key role in the selection of abatement options within the N-ZIP model.

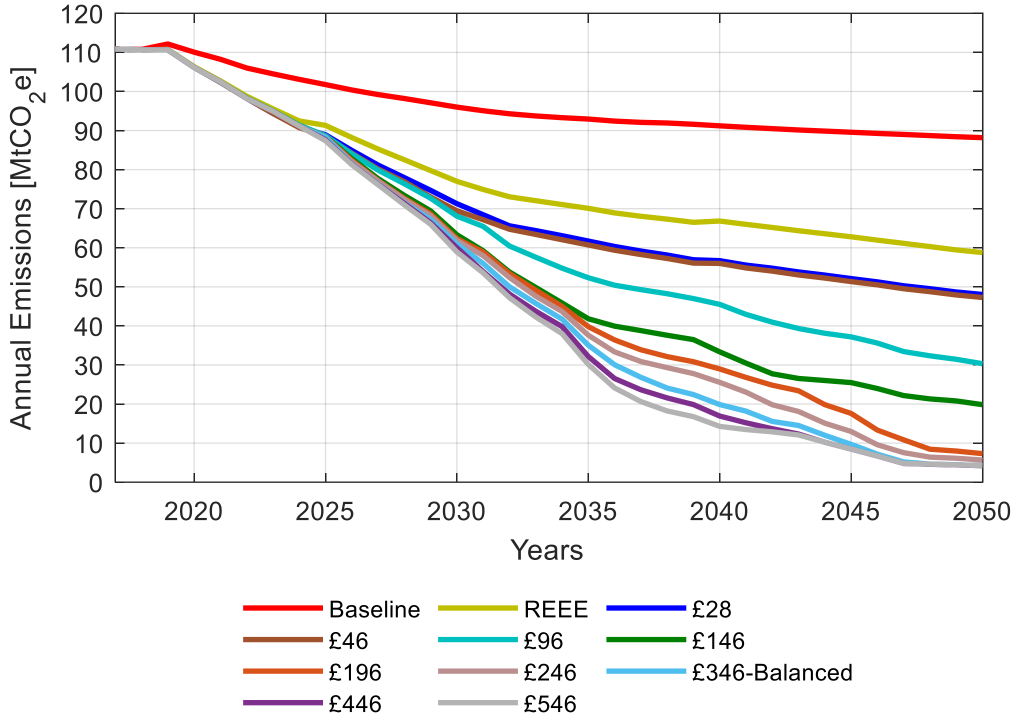
Within the Balanced scenario, the main carbon price is based on the 2019 BEIS Green Book's "high untraded price profile". This increases from £104/tCO_2 in 2020 to £346/tCO_2 by 2050 as shown in Figure 16. Where we have explored the effect of alternative carbon prices, these are modelled as different 2050 prices (shown in Figure 16 and the subsequent figures in this section). A linear increase is assumed to the final 2050 prices from the 2030 price of £121/tCO_2 (i.e. as in the Balanced scenario) except where the final 2050 carbon price is lower than this value (£121/tCO_2). In these cases, a flat value is assumed in all years.

Figure 16 Carbon price scenarios over years used in this paper



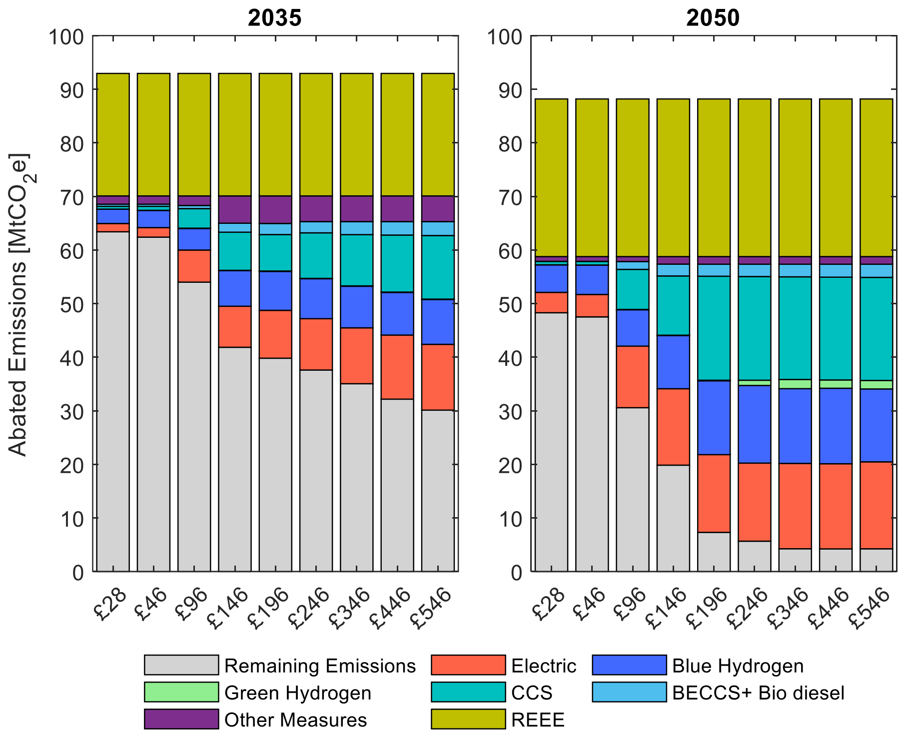
As shown in Figures 17 and 18, a carbon price greater than that in the Balanced scenario (£346/tCO_2 in 2050) brings forward the deployment of abatement options, while price trajectories that reach less than £196/tCO_2 in 2050 have significantly higher remaining emissions in 2050. Setting carbon prices considerably lower (£28 to £46/tCO_2) results in 40% more emissions remaining in 2050 than in the Balanced scenario.

Figure 17: Effect of carbon price on GHG emissions



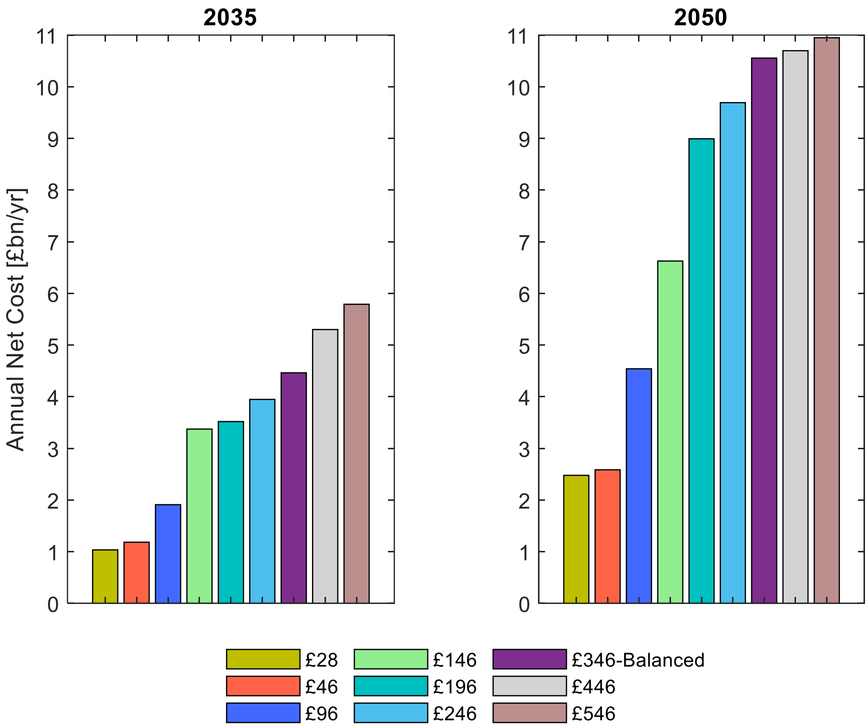
Until 2035, the main differentiation in emissions occurs as the price profiles increase from £46/tCO_2 to £146/tCO_2; there is little apparent emissions benefit due to higher price profiles during this period. Although this is partially due to these profiles being the same until 2030, it also reflects the delays that are inherent before the widespread deployment of certain technologies is possible. In a sense, this reflects exogenous parameters that affect availability rather than results that are endogenously modelled, but these conditions may also represent real delays in what is possible. Bottlenecks (such as infrastructure, technology development and supply chain limitations) might constrain achieving industrial emissions below about 40 MtCO_2e/yr until around 2035. By 2050, carbon price profiles below £200/tCO_2 start to result in progressively higher emissions; decreasing the 2050 price to £146/tCO_2 results in around 20 MtCO_2e/yr in 2050 (compared to around 8 Mt CO_2e/yr for scenarios with higher carbon prices). Carbon prices greater than the Balanced scenario (£346/tCO_2 in 2050) have no additional effect on the modelled 2050 emissions and relatively little additional effect on those in earlier years. It appears that some abatement measures are viable with low carbon costs (i.e. maintaining £28/tCO_2 to 2050) but that additional measures do not then become viable until the price profile increases beyond £46/tCO_2.

Figure 18: Effect of carbon price on abatement technologies adopted[8]



[8] The price on the x-axis of this graph refers to the carbon price in 2050. Hence, the carbon prices in 2035 are lower in most scenarios (except for the £28, £46 and £96 scenarios where carbon prices are flat across all time periods and therefore the 2035 and 2050 values are the same).

Figure 19: Effect of carbon price on net cost



The effect of carbon price on net costs follows a similar pattern to the abatement that is achieved (Figure 19). There is a notable jump in 2035 net costs that occurs when the price profile increases from £96/tCO_2 to £146/tCO_2. In 2035, the £546/tCO_2 carbon price results in a £1.32bn investment cost increase compared to the Balanced scenario cost. This results in 5 MtCO_2e more emission reductions in 2035 compared to the Balanced scenario (see Figure 17). This is associated with the adoption of hydrogen and CCS that the carbon price enables by that point. Higher carbon prices also bring forward the adoption of electric technologies, but have less effect on the magnitude of their eventual role.

In Figure 20, as the carbon price increases from £28 to £546/tCO_2, the share of natural gas is gradually decreased; by 35% in 2035 and 78% by 2050. In contrast, electricity and hydrogen consumption increases in both years as the carbon price increases, reaching nearly 132 TWh and 82 TWh respectively in 2050. The primary bioenergy and solid fuel consumption are nearly steady at around 50 TWh and 27 TWh by 2050 respectively.

Figure 20: Effect of carbon price on fuel consumption

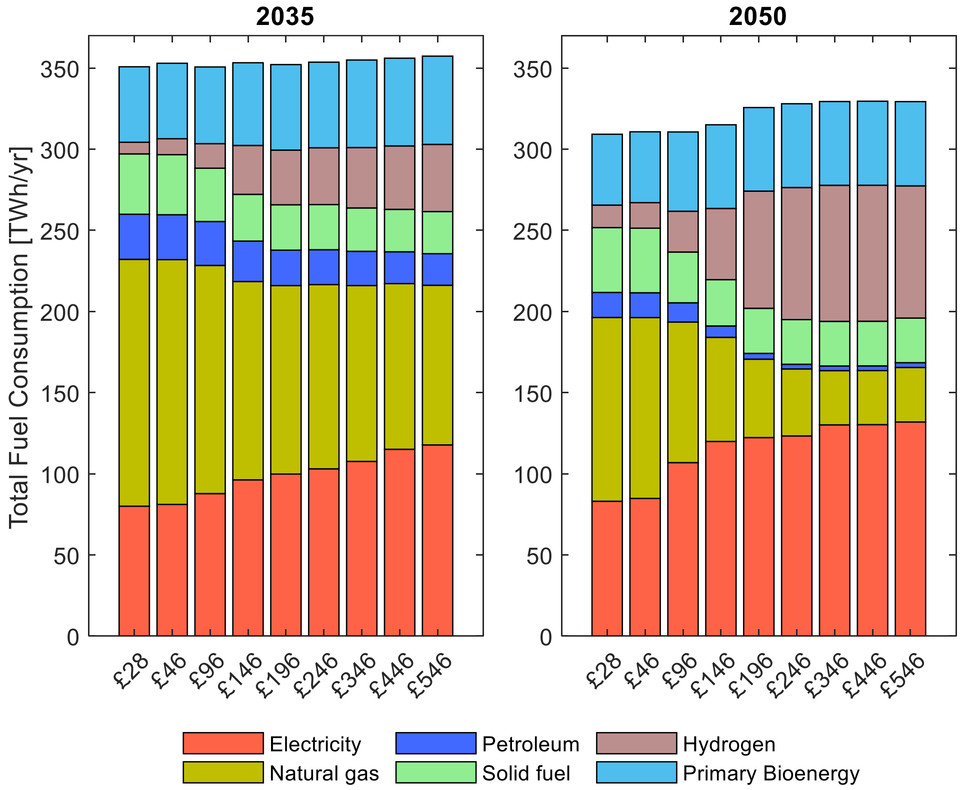
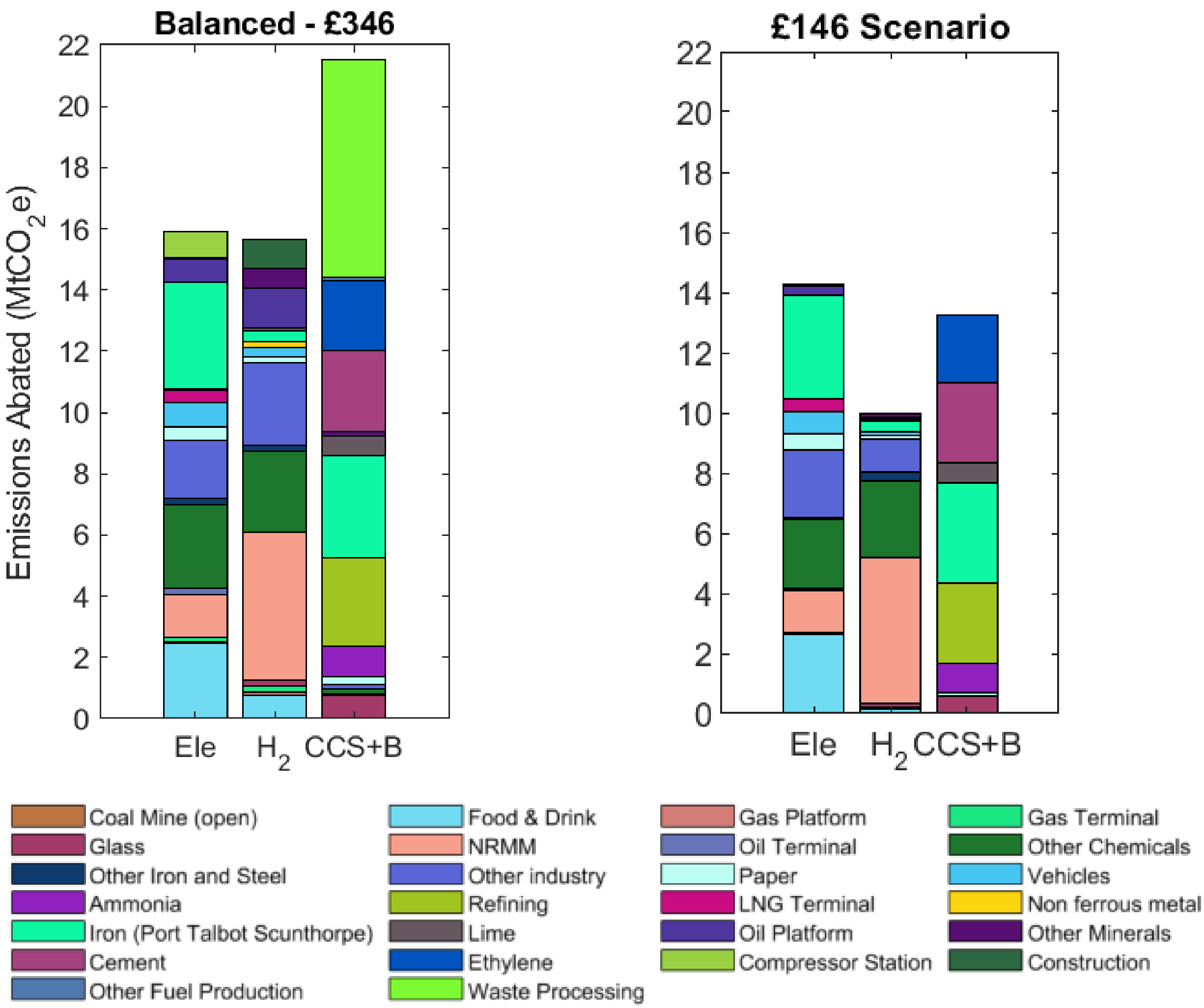


Figure 21 shows that a lower carbon price profile (£146/tCO_2 vs the £346/tCO_2 profile for the Balanced scenario) results in fewer sectors employing either hydrogen or CCS. However, there is far less impact on the sectors that achieve abatement through electrification as these options are less reliant on the support of a higher carbon price. Hydrogen and CCS with bioenergy technologies abate 37.5% and 40% fewer emissions respectively compared to electrical technologies at the lower carbon price of £146/tCO_2. This affects the uptake of CCS technologies for the Waste Processing sector[9] and the hydrogen technologies particularly in the Food & Drink, Other industry, and Oil Platforms sectors. The cost-effectiveness of some of these options is relatively sector-specific (i.e. most of the difference in the results between the two cost profiles is due to some sectors adopting or not adopting hydrogen and CCS, rather than primarily due to all of the sectors using them a little, more, or less).

[9] Although another study finds that the cost of carbon capture utilisation and storage is competitive with other abatement options for the Waste Processing sector, see https://es.catapult.org.uk/reports/energy-from-waste-plants-with-carbon-capture/.

Figure 21: Effect of carbon price on sectoral abatement (2050)

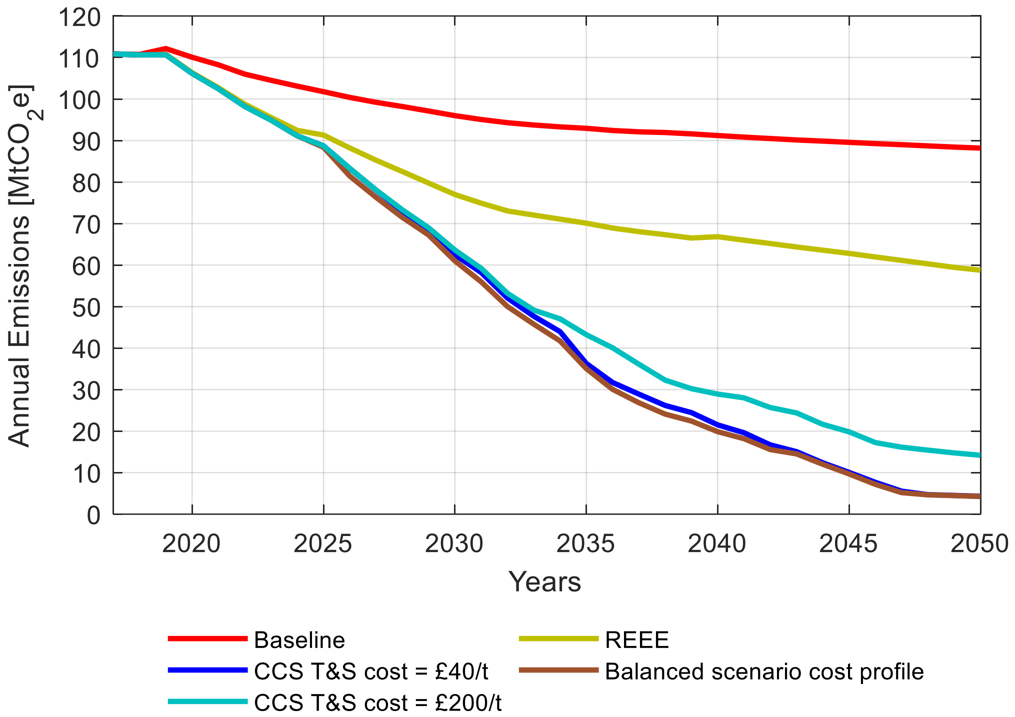


4.4 Carbon capture and storage

In this subsection, we investigate the modelled effect of making CO_2 T&S infrastructure less accessible to industry. Rather than implement this as a hard constraint on the capacity of the relevant infrastructure (see discussion in Appendix B), we increased the costs associated with T&S such that it was a minimum of either £40/tCO_2 or £200/tCO_2. By contrast, these costs typically reduce to around £4/tCO_2 to £13/tCO_2 (location dependent) by 2030 in the Balanced scenario.

The modelled results in Figure 22 show very little effect of increasing the cost of carbon T&S to £40/tCO_2. This demonstrates that the economic desirability of this infrastructure (and the options it enables) is likely to be robust to considerable increases in its eventual cost.

Figure 22: Effect of CO_2 T&S costs on GHG emissions



If the cost of CO_2 T&S is increased to £200/t (i.e. a cost that should be largely prohibitive to CCS), we see that CCS is not selected in many cases. In the majority of these cases, the model does not find alternatives. A reduction in CCS abatement results in almost an equivalent reduction in overall abatement by 2050 (Figure 23). However, while the use of CCS is delayed (with no major adoption in 2035) and reduced (capturing less than half the CO_2 in 2050), it is not completely eliminated in the model outputs. Within the modelled assumptions, the CO_2 T&S is both vital to industrial decarbonisation and would sometimes be selected even if very expensive.

Increasing the cost of CO_2 T&S leads to some increase in net costs (Figure 24) but little difference in the overall fuel consumption mix (Figure 25). If CO_2 T&S costs/availability also impinged on blue hydrogen production (this functionality is available in N-ZIP but was not used in this scenario) then we would expect further increases in costs and a greater proportion of green (electrolysis) hydrogen relative to blue (natural gas reforming with CCS) hydrogen.

Figure 23: Effect of CO_2 T&S cost on abatement selected

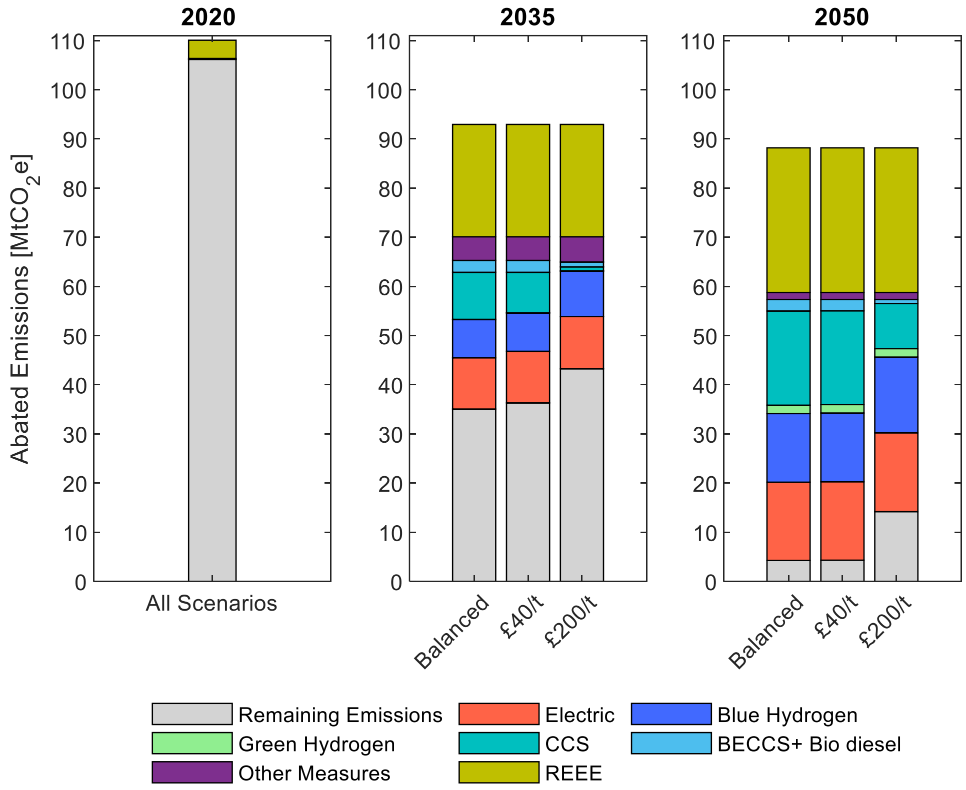


Figure 24: Effect of CO_2 T&S costs on net costs

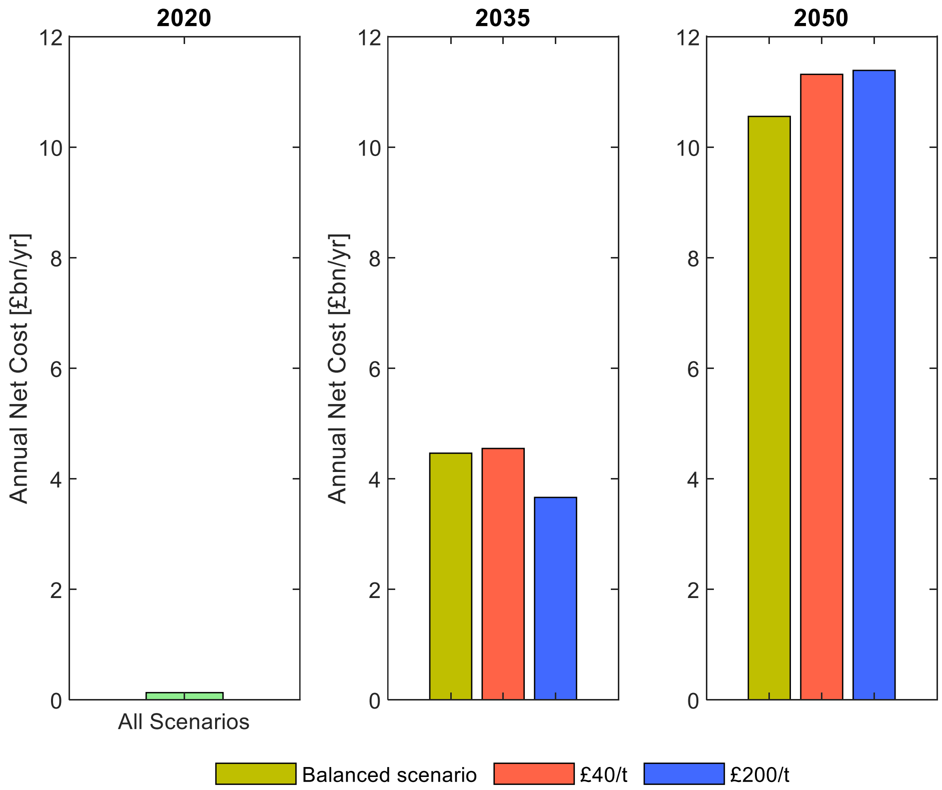
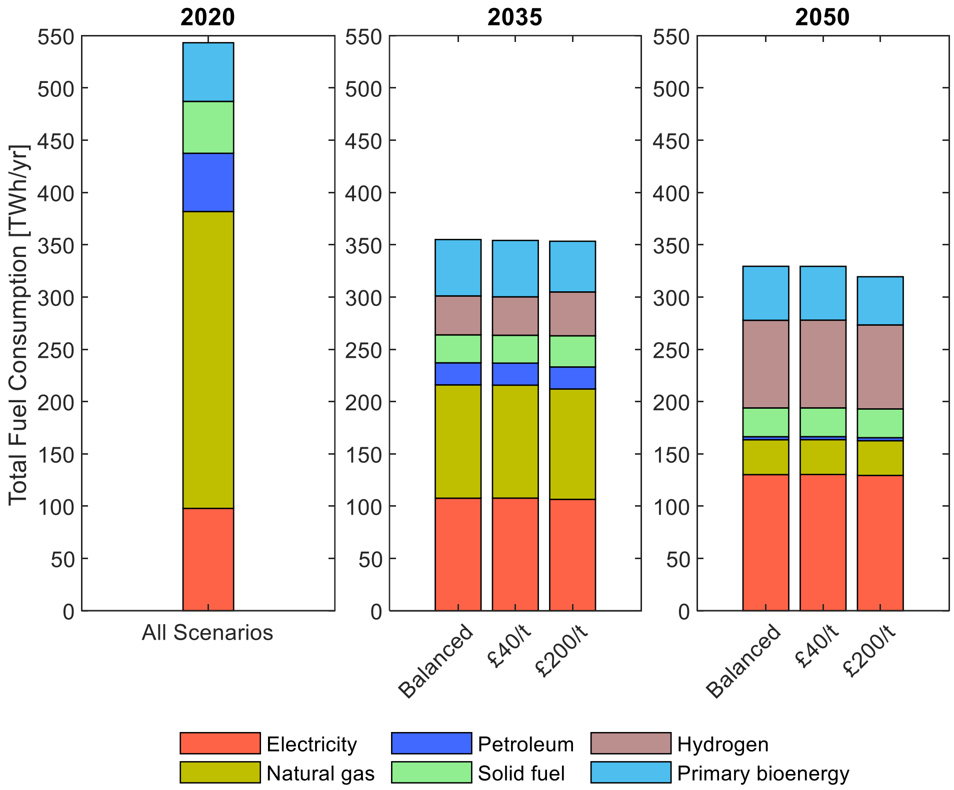


Figure 25: Effect of CO_2 T&S costs on fuel consumption



4.5 Energy costs

We now consider the effect of changing the relative costs of fuel on the model results. First (in this subsection), we examine the effect of changing the price of energy vectors (including electricity, biomass, coal, gas, and oil but excluding hydrogen as this is explored further in the next subsection). To give a wide sensitivity range, successive runs halve, double and quadruple these prices.

While the model outputs in terms of emissions are relatively insensitive to these variations (Figure 26), it is interesting that a small amount of abatement is brought forward with either an increase or a decrease in energy costs.

Figure 28 shows that as the fuel cost (excluding hydrogen) is increased to double and quadruple, the net cost (total abatement measure costs minus total baseline costs) is reduced in 2035 and 2050 compared to the Balanced scenario as the abatement measures using these fuels are used less (due to higher fuel cost) for decarbonising industry processes.

Figures 27 and 29 show that the model progressively favours blue hydrogen over electricity as the price of the electricity (and other fuels excluding hydrogen) increases (and vice versa). This can also be observed at a sectoral level (Figure 30) – the abatement options for several sectors (in 2050) are simply moved from electrification to hydrogen as the relative cost of the electricity is increased. This is not surprising. Future iterations of the model could consider having more explicit linkages between the price of blue hydrogen and natural gas, and between the price of green hydrogen (hydrogen produced through electrolysis) and electricity.

Figure 26: Effect of energy prices on GHG emissions

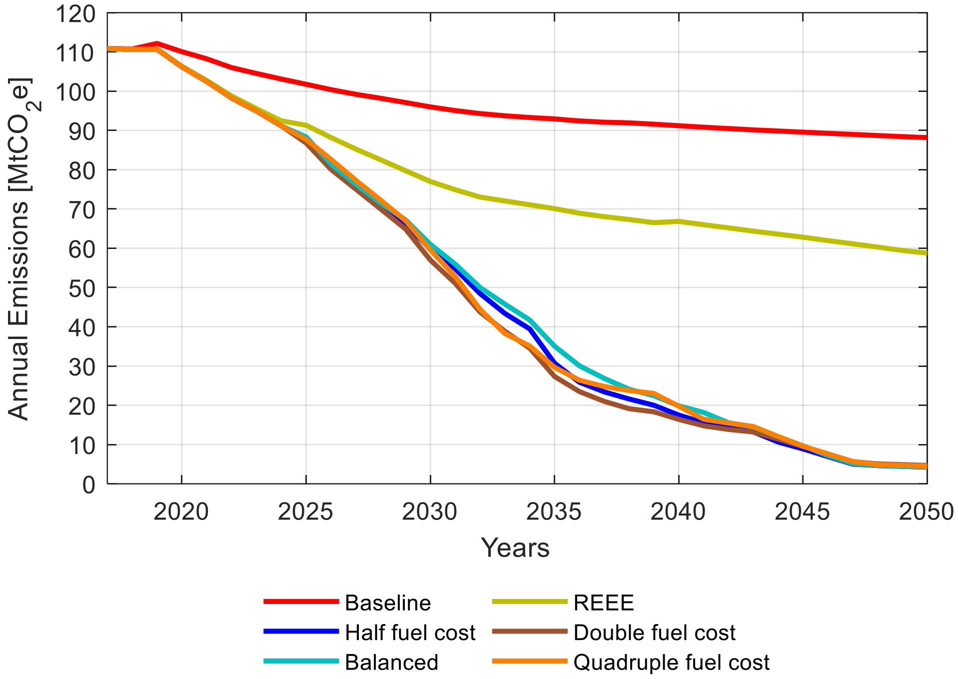


Figure 27: Effect of energy prices on abatement options selected

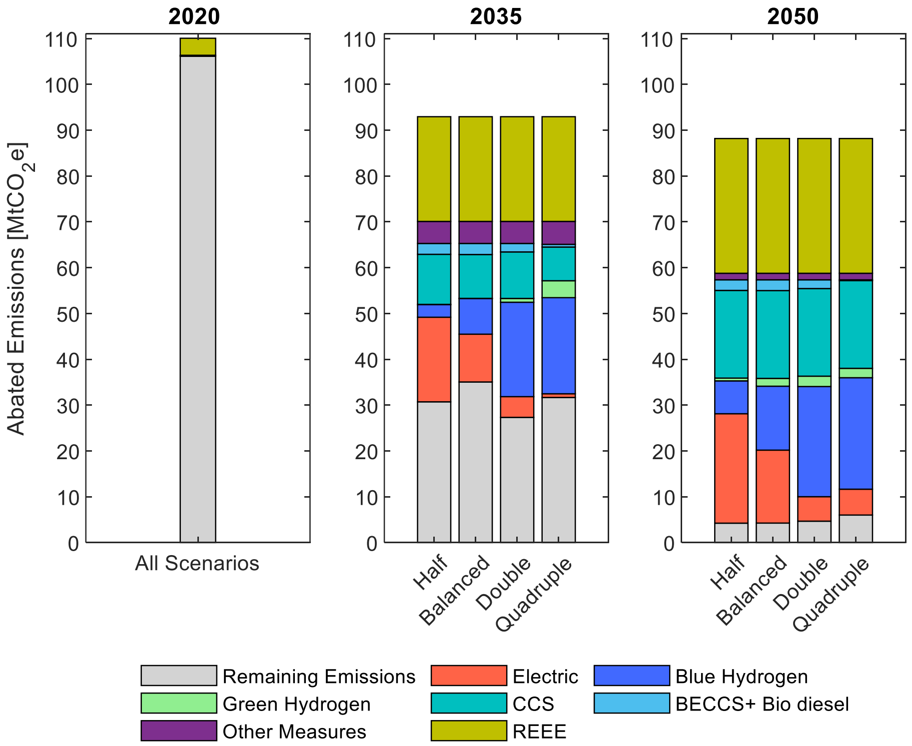


Figure 28: Effect of energy prices on net costs

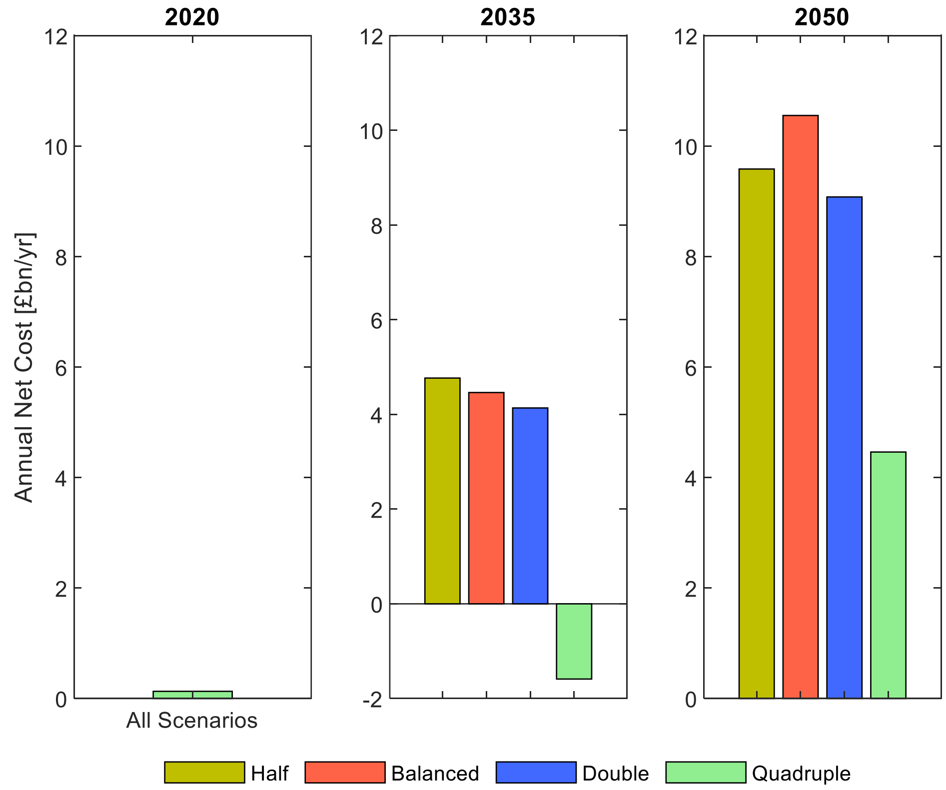


Figure 29: Effect of energy prices on fuel consumption mix

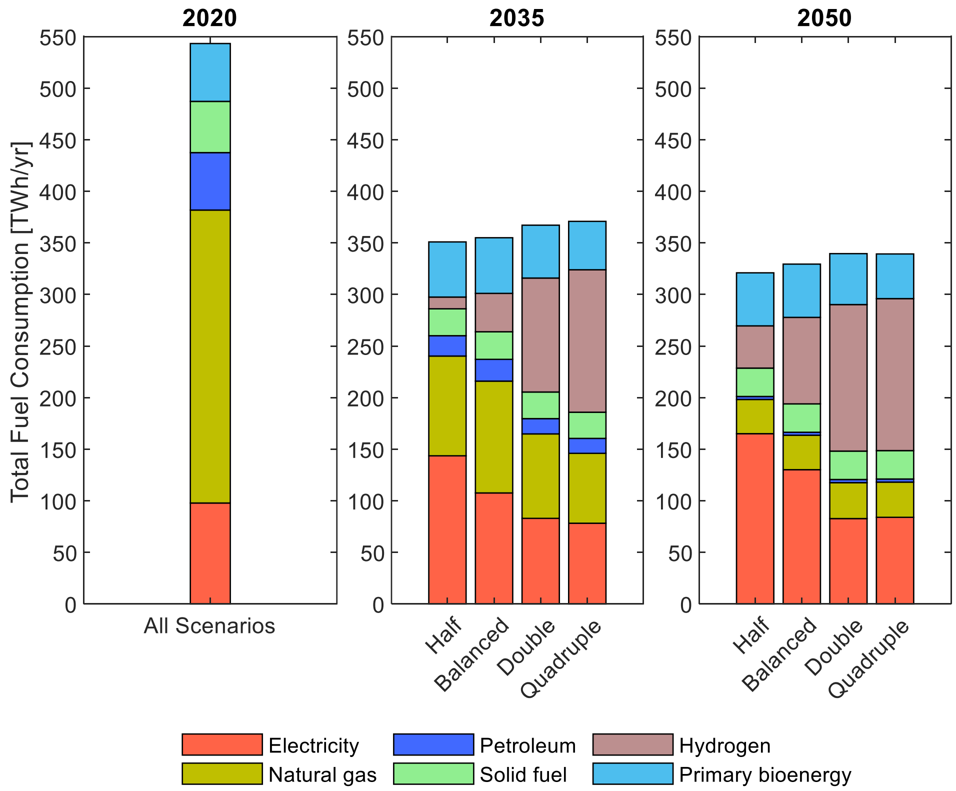
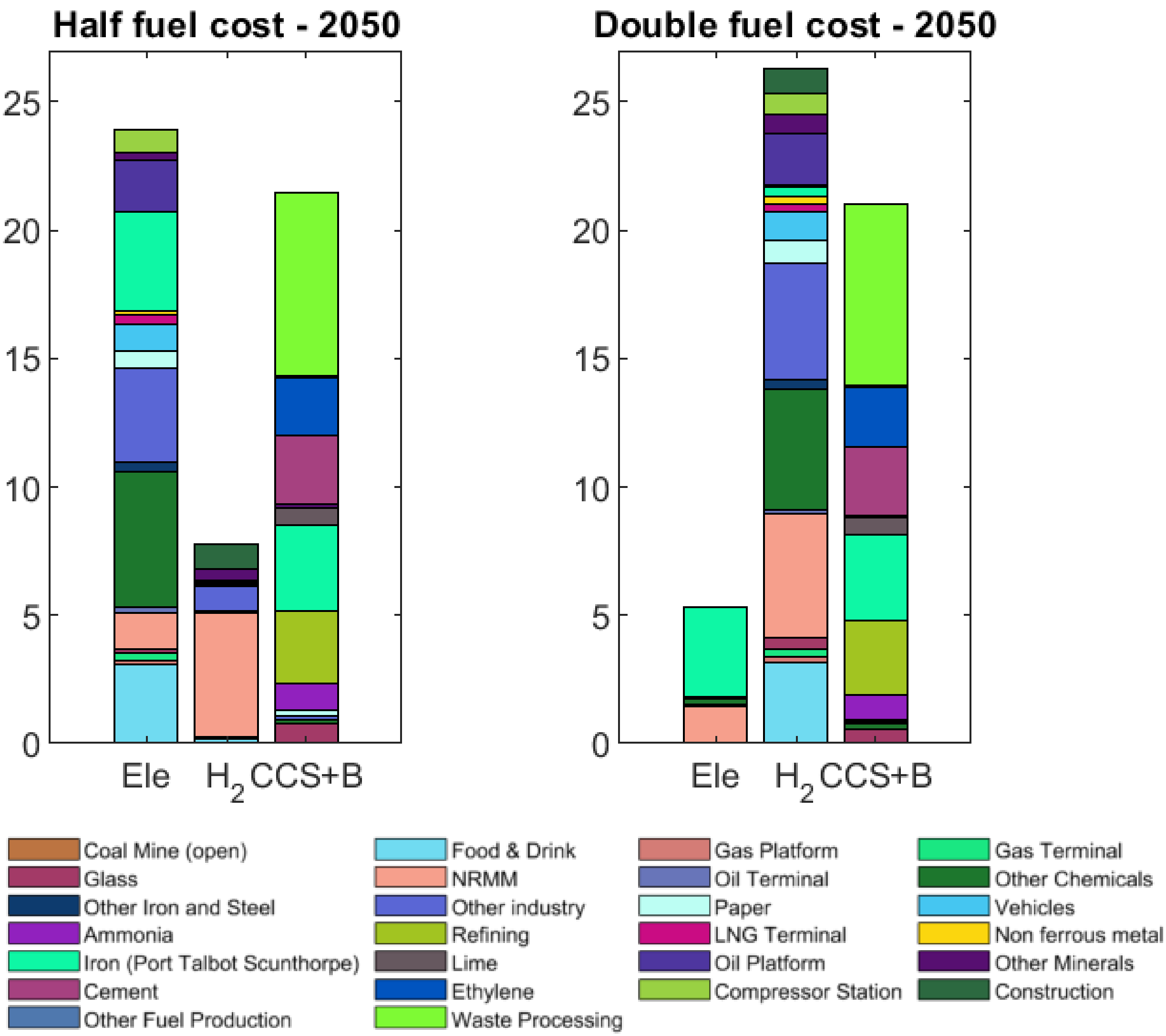


Figure 30: Effect of energy prices on sectoral abatement options

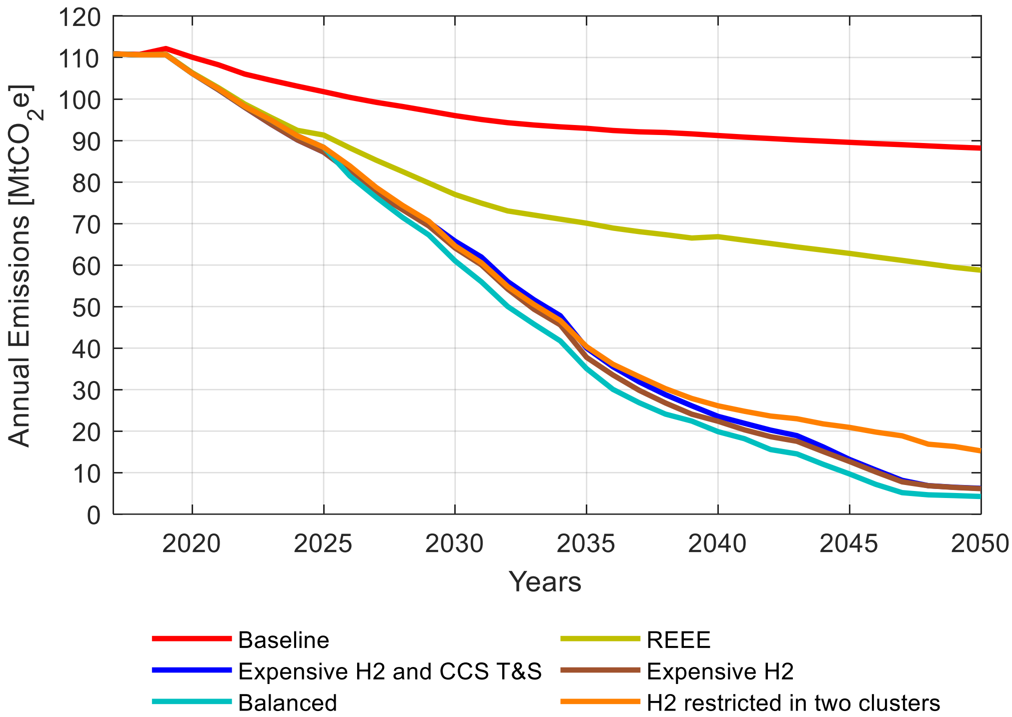


4.6 Hydrogen availability

In this subsection, we expand the sensitivity analysis on the price of energy vectors to consider the effect of varying the price or availability of hydrogen on the model's outputs. Again, this is implemented by varying the cost of hydrogen (at either all locations or for selected clusters), rather than by applying hard constraints on hydrogen availability.

In the "Expensive H2" scenario, the minimum production cost of hydrogen was increased to 12p/kWh – i.e. greater than the cost of electricity. In the "Expensive H2 and CCS T&S" scenario, this was combined with a cost increase for CO_2 T&S to a minimum of £40/tCO_2 (i.e. as per scenario in subsection 4.4). In the "Expensive H2 in two clusters" scenario, the cost of hydrogen was increased to 200p/kWh for all locations except for Humberside and South Wales; i.e. this is a prohibitive cost that is used in order to consider the effect of limiting hydrogen (except at those two clusters), where equivalent hard constraints were found to be problematic to the model.

Figure 31: Effect of hydrogen attractiveness on GHG emissions



The scenarios with higher hydrogen costs result in slightly greater remaining emissions in most cases and significantly greater emissions where hydrogen is limited to two clusters (Figure 31). In Figure 32, it can be seen that if hydrogen costs are significantly increased, the model still achieves some abatement through using it, but replaces the majority of hydrogen with electrification. The aggregate role of CCS is largely unaffected. This result is minimally affected if the cost of CO_2 T&S is also increased (i.e. consistent with subsection 4.4, but noting that there is no apparent "tipping point" under these parameters). Total net costs (i.e. summed across years) increase as options are made more expensive (see Figure 33). In the case of expensive hydrogen, this increase occurs later, whereas in the case of "unavailable" hydrogen the additional net costs are incurred earlier.

Figure 32: Effect of hydrogen attractiveness on abatement options selected

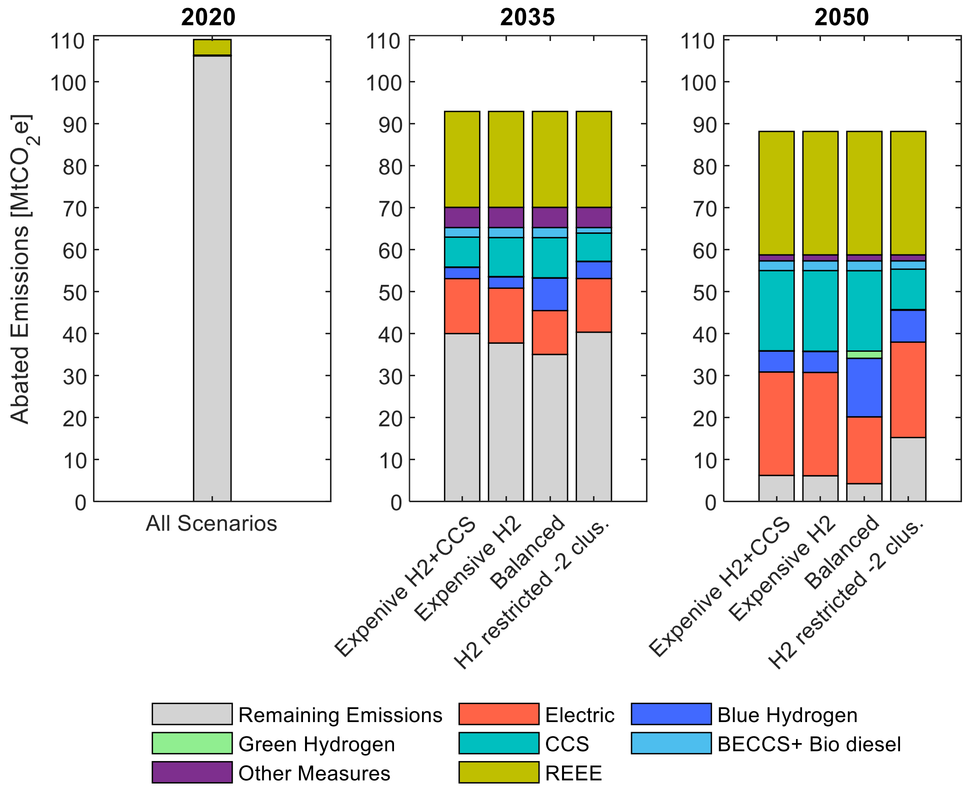
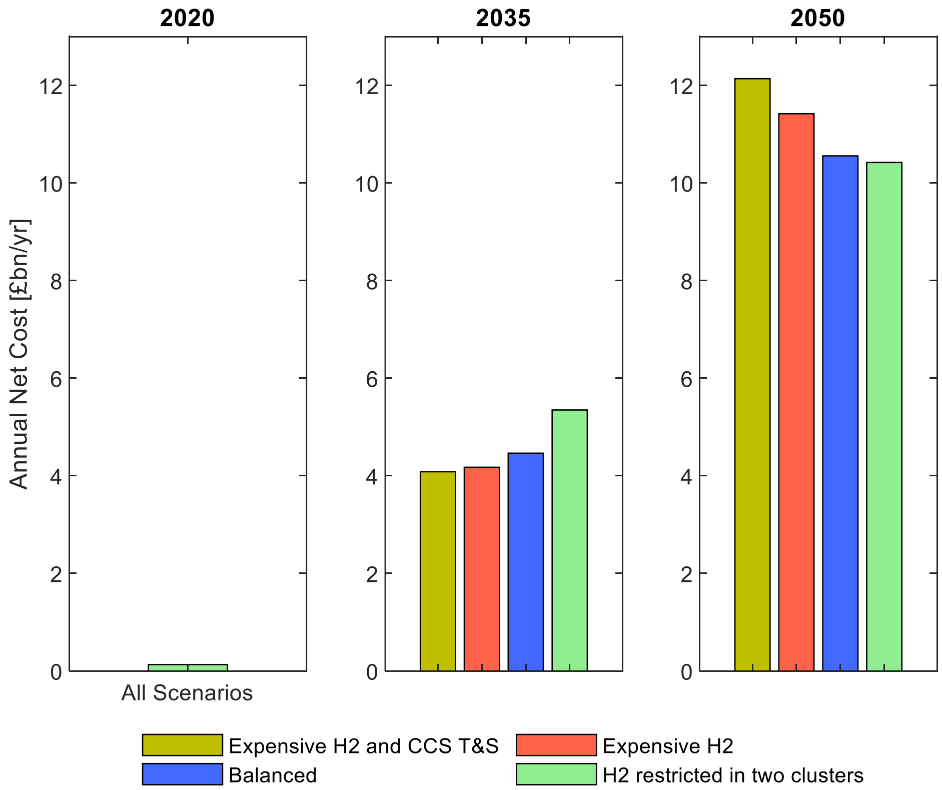
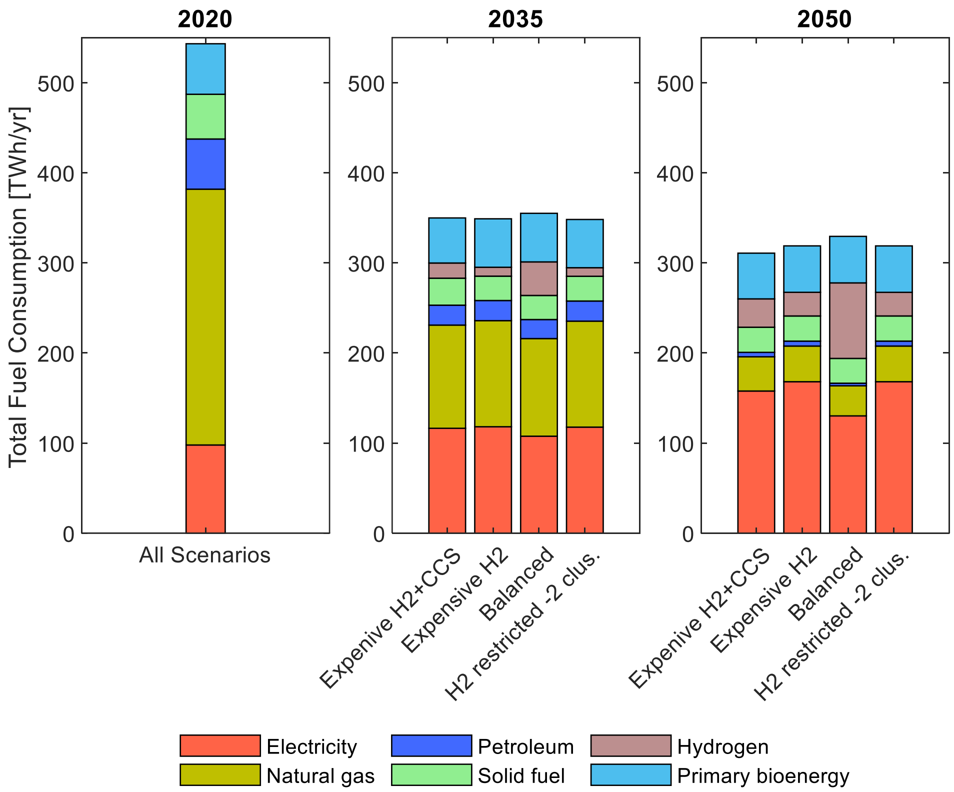


Figure 33: Effect of hydrogen attractiveness on net costs



In line with the findings of Figure 31, in Figure 33, as hydrogen production becomes more expensive, hydrogen fuel share is reduced by at least double compared to the Balanced scenario in 2050.

Figure 34: Effect of hydrogen attractiveness on fuel consumption

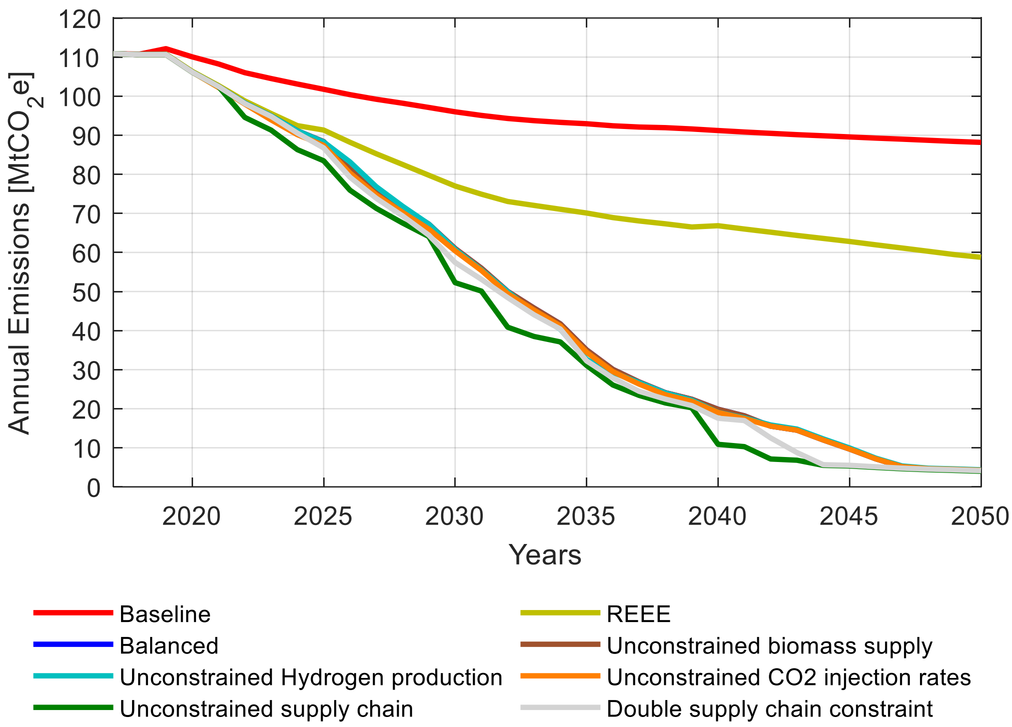


4.7 Other model constraints

In this subsection, the effect of relaxing several modelled constraints is explored. These constraints relate to the production of hydrogen, the supply of biomass, the supply chain for the decarbonisation technologies, and the CO_2 injection rate (into geological storage). When the N-ZIP model runs, it first selects the decarbonisation option with the greatest NPV for each emissions source (subject to certain parameters such as infrastructure roll-out rates), and then secondly applies constraints relating to these four considerations (before iterating). This second step of applying constraints forces some sites to select options with a lower NPV. By relaxing these constraints, this subsection, therefore, explores both the effect of the constraints on the decarbonisation pathway, but also the design of the approach that N-ZIP takes when deciding which sites will be forced to select decarbonisation options with lower NPVs.

Figure 35[10] shows that individually relaxing the hydrogen production, biomass supply and CO_2 injection constraints has almost no effect on the modelled results. The supply-chain constraints do not affect the final decarbonisation achieved but do affect the rate at which this occurs.

Figure 35 Effect of supply constraints on GHG emissions.



The similarity between the results for the Balanced scenario and those with relaxed constraints means that the methodological approach that has been employed to apply these constraints within N-ZIP is less critical to the final results that were derived with them. Further refinement of the optimisation process for selecting the sites that are affected by these constraints is not beneficial (for comparable scenario parameters).

While the hydrogen production and CO_2 injection constraints have only minor effects, it should be noted that N-ZIP will have already applied additional constraints relating to the availability of pipeline infrastructure to transport them as part of "step 1" (i.e. in determining whether they are valid options for each site). Within the parameters used, this indicates that this infrastructure is the bottleneck, rather than that the rate of production and injection is not important.

Relaxing the supply-chain constraints results in a more step-like decarbonisation pathway. At certain points, key abatement technological options become available /

[10] The 'Balanced' and 'Unconstrained biomass supply' scenarios exactly match in terms of the remaining emissions values, hence the blue colour is not visible in the figure.

cost-effective. In those years (e.g. 2040) a large number of sites would adopt that technology if not for the constraint. With the supply-chain constraint in place, a similar level of decarbonisation is eventually achieved but this is spread over a number of years. This is not unreasonable; it is unrealistic to expect a technology to be adopted instantly across all sites for which it is relevant. However, the step-like pathway does highlight the importance of certain key abatement options that are assumed to become available and cost-effective at future dates. De-risking the availability of these options is sensible. This effect also emphasises the importance of the supply-chain for these options (and its ability to scale-up); further investigation into the actual market dynamics that might occur is warranted.

5. Heat decarbonisation

In this section, we focus on the abatement of GHG emissions associated with the provision of heat, as this is a key issue for industry. This includes processes that use both high- and low-temperature heat[11].

In Figure 36 we can see that a range of abatement options are used across industry in the Balanced scenario – with hydrogen and electrification playing almost equal roles, and CCS abating almost as many emissions as the first two combined. A net-zero consistent pathway for UK industrial emissions requires heat provision to be almost completely decarbonised.

However, if we disaggregate between high- and low-temperature processes[12] (Figures 36 and 37), we see that the remaining abatement options (after REEE is applied) divide neatly between them. Hydrogen and electrification are used to abate low-temperature processes. For high-temperature heat, the most important emissions reductions come from CCS, with electric arc furnaces being the only significant high-temperature electrification option used. Because of this, it is the high-temperature processes that have lower abatement (i.e. have greater residual emissions) if the cost of CO_2 T&S is increased.

The fuel use for high- and low-temperatures processes is depicted in Figures 39 and 40 respectively. A large decrease in the uptake of natural gas is noted for high-temperature processes with smaller increases in the use of solid fuel and electricity starting from 2040 and 2033 respectively. For low-temperature processes, the use of both hydrogen and electricity increases. The increase in the use of hydrogen is slightly greater but because electricity is already in use, it ends up satisfying approximately two-thirds of the demand for low-temperature heat, with the remaining third through hydrogen

[11] High-temperature heat refers to processes operating above 240°C and low-temperature heat to processes below that temperature.
[12] The disaggregation of heating processes was done based on the heat classification (high, low, both) in the model's assumptions log (Element Energy, 2021).

Figure 36: Annual emissions for all heating processes (Balanced scenario)

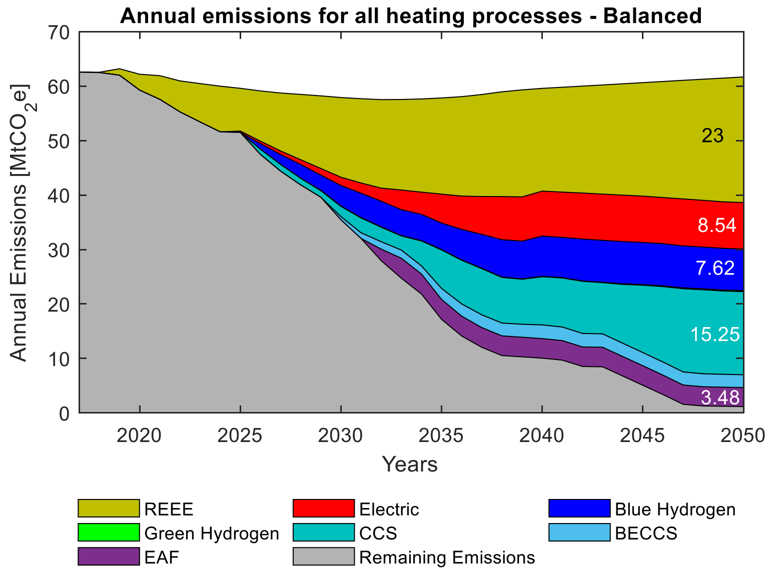


Figure 37: Abatement for high temperature processes

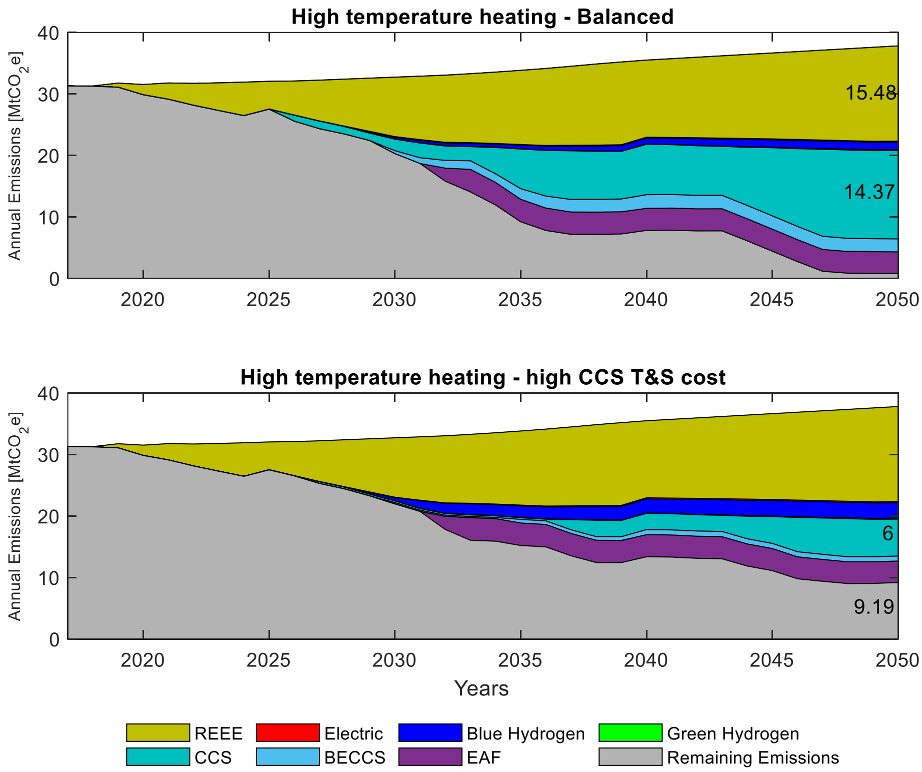


Figure 38: Abatement for low temperature processes

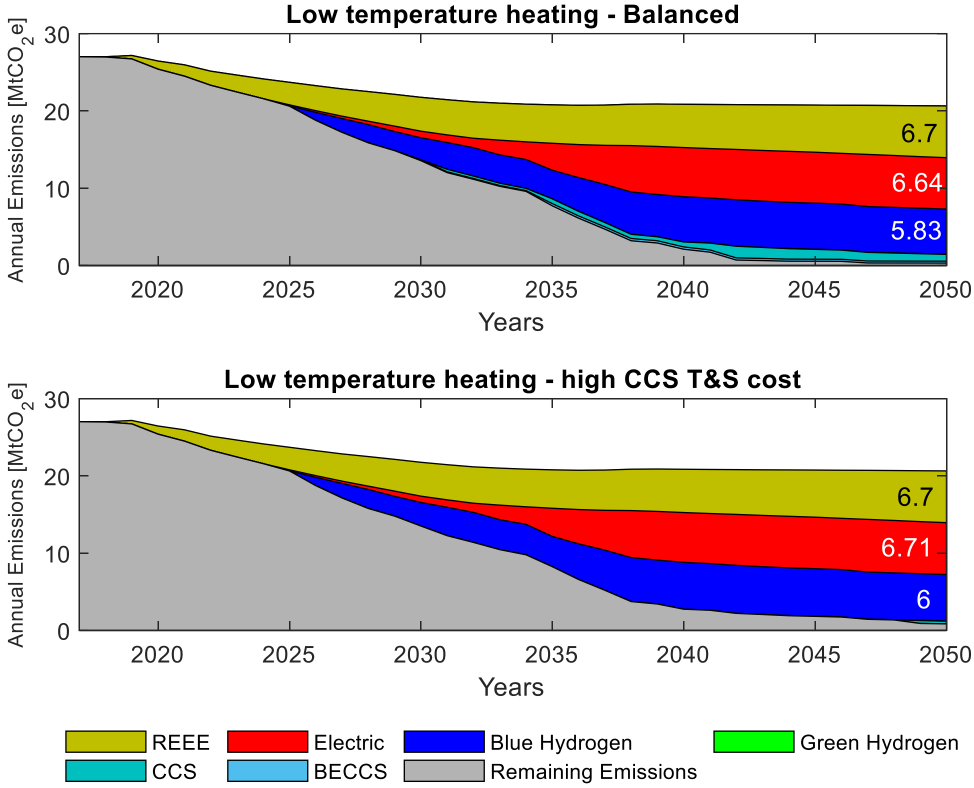


Figure 39: Fuel use for high temperature processes

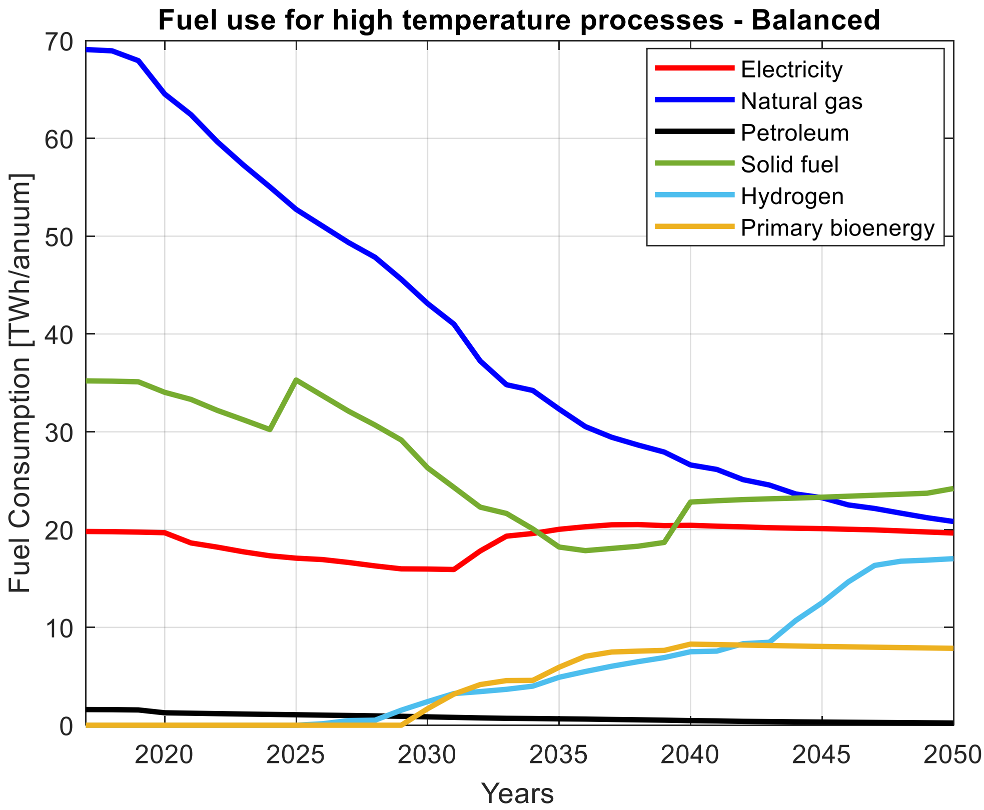
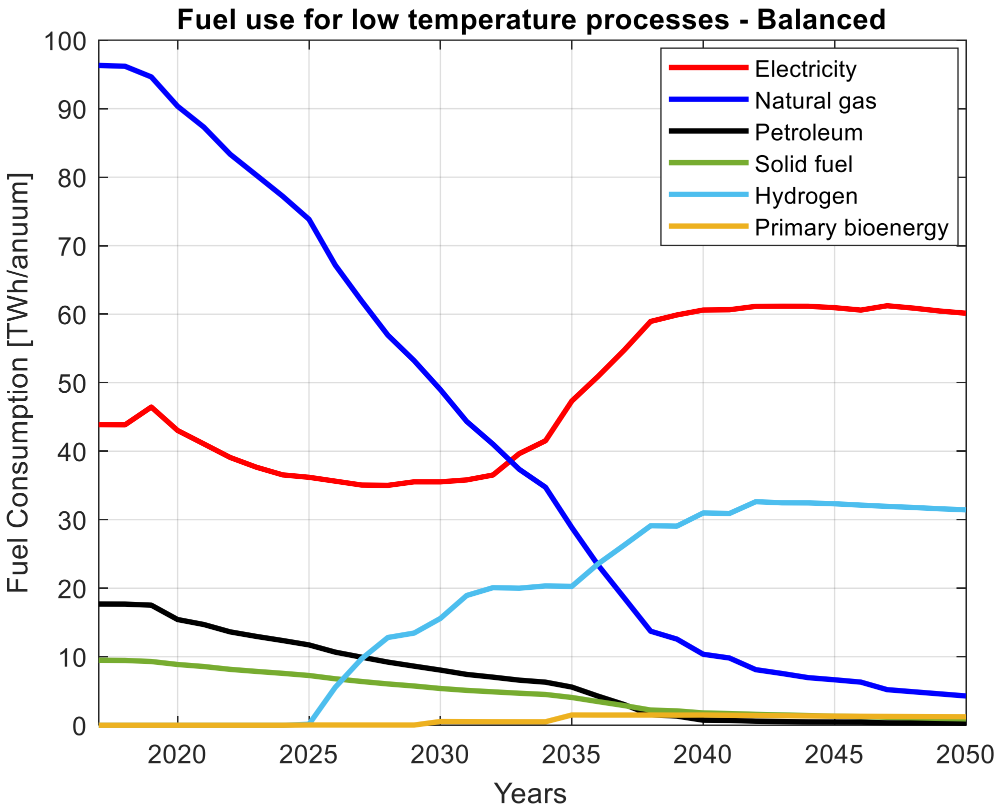


Figure 40: Fuel use for low temperature processes



6. Conclusions

The N-ZIP model can be used to provide a comprehensive assessment of UK industrial emissions abatement pathways and the choice of them that is (nearly) optimal from an NPV perspective. It takes account of carbon prices, the availability of different fuel and technology options, and the projected future deployment of hydrogen and CO_2 infrastructure. These results can also be geographically disaggregated, although this feature has not been explored in the scenarios presented here.

Model robustness. The various aspects explored in this study indicate that the N-ZIP results are generally robust to relatively wide variations in the input parameter assumptions that we have explored. This evidence strengthens the case for the way in which the CCC and BEIS have used the model and its results. Like any model, the various input parameters are critical to the validity of its results. The process used to populate these parameters (e.g. technology costs) appears robust, but further work could refine them.

Treatment of REEE. The current model formulation takes industrial activity projections as exogenous inputs and then adjusts these with factors relating to REEE that are also exogenously defined. This means that currently there are no costs associated with making REEE improvements and so no analysis of the trade-off in reducing emissions in industry between reducing the demand for energy and reducing its carbon intensity. The model sensitivities show that variations in the assumptions about RE can change the net cost of abatement in 2050 by about 13.5% and so have an important influence on the results. However, these levels of RE are purely illustrative and ideally further work would explicitly evaluate the most appropriate levels of RE (and EE) in an optimal industrial decarbonisation strategy. One option to achieve this would be to endogenise information about the relationship between costs and impacts on energy demand within the model.

Role of CCS. The model indicates that CCS will provide a key contribution to industrial decarbonisation in the UK. Subject to the modelling perspective and parameters, CCS would remain the chosen technology to abate a significant proportion of emissions, even if transport and storage costs were far greater than those currently assumed in the model. Additionally, if CCS is not available then the model fails to decarbonise industry to the targeted level. This result has significant policy implications and further work should be undertaken to explore whether the model incorporates the full range of future alternative abatement options to CCS, particular for dispersed sites where CCS may face substantial practical and economic challenges.

Costs of abatement. The model demonstrates the importance of the assumed carbon price trajectory to the level of decarbonisation achieved. The ‘Balanced’ scenario of the CCC uses the Green Book “high untraded” profile, in which CO_2 prices rise from £104/tCO_2 in 2020 to £346/tCO_2 in 2050. While a few decarbonisation options are cost-effective with low carbon prices (below about £30/tCO_2), the majority of decarbonisation options are only cost-effective once carbon-price trajectories reach around £200/tCO_2 (in 2050). Increasing the carbon-price above the default trajectory has a little additional overall effect on CO_2 abatement, indicating that the majority of industrial emissions abatement have costs that are lower than that implied by the carbon price assumptions currently used. However, if the carbon-price trajectory is reduced below £200/t (in 2050), then abatement options for a large proportion of emissions are progressively delayed or reduced.

Supply-chain constraints. The model applies constraints to the rate at which decarbonisation technologies can be deployed. The approach seems appropriate to the questions that N-ZIP addresses. However, these considerations have a significant effect on the profile of the pathway, and therefore the rate of decarbonisation, and so warrant further exploration.

Broader implications. The N-ZIP model has been developed to address specific questions about the feasibility of deep decarbonisation of UK industry and consequently, its results should not be interpreted too broadly. It takes a societal perspective as its main approach as this is appropriate to answer questions around whether projected UK industrial activity could be decarbonised over the next 40 years, the most cost-effective mix of technologies that might achieve this (for a given set of assumptions) and the related costs to the UK. Within this context, it does not claim to be answering questions concerning the most appropriate mechanisms to facilitate these futures, the likelihood of their success, or any knock-on effects from them. For example, decarbonisation might result in more (or less) significant restructuring of industrial activity. N-ZIP does not explore either the extent to which more fundamental changes to the UK's industrial structure (such as the closure of key large industrial plants) might affect industrial decarbonisation pathways, or the effect that policies to deliver decarbonisation might have on the relative competitiveness of these sectors.

Future work. The N-ZIP model is currently computationally expensive where each run takes at least 3.5 hours to finish using a high-specification computer. Future work by UKERC will explore the possibility to recode the Excel-based model in a different programming language such as Python, R, or Julia. The possibility to link a more efficient and/or different version of N-ZIP with the UK TIMES model could also explored to investigate the interaction of the industrial sector with the wider economy in terms of the residual emissions, applied technologies, supply chain, and carbon pricing.

Other suggestions for future work include:

- Identifying whether there are additional abatement technologies for dispersed industrial sites that are not currently included in the model.
- Exploring supply chain links (for example, linking prices of blue hydrogen with natural gas, and accounting for biomass trade-off with other economy sectors).
- Analysing the life-cycle implications of industrial decarbonisation.

7. References

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8. Appendix A: Scenario results

This appendix presents the full set of the results for some of the scenarios explored in section 4.

8.1 Resource efficiency

The results for the “Resource Efficiency 0% and 150%” scenarios are presented in Figures A1-A3.

Figure A 1 Annual emissions for UK industry by technology type - (left): Resource Efficiency 0%, (right): Resource Efficiency 150%

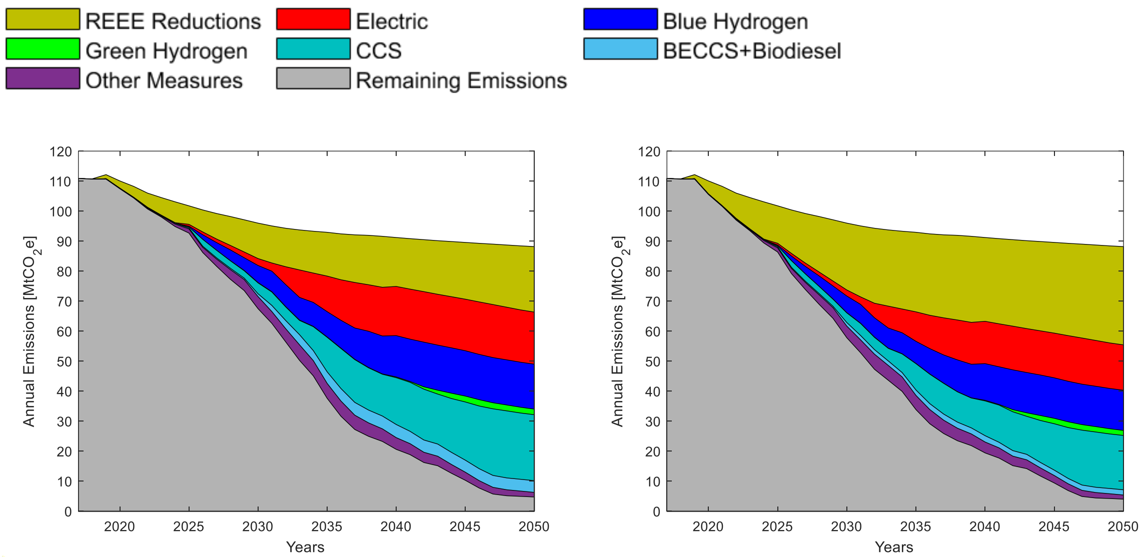


Figure A 2 Abatement measures annual net cost - (left): Resource Efficiency 0%, (right): Resource Efficiency 150%

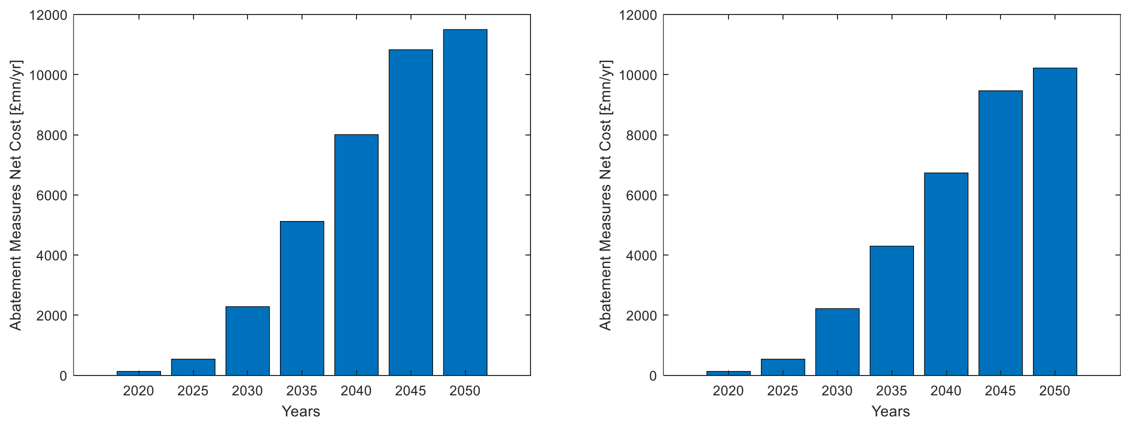
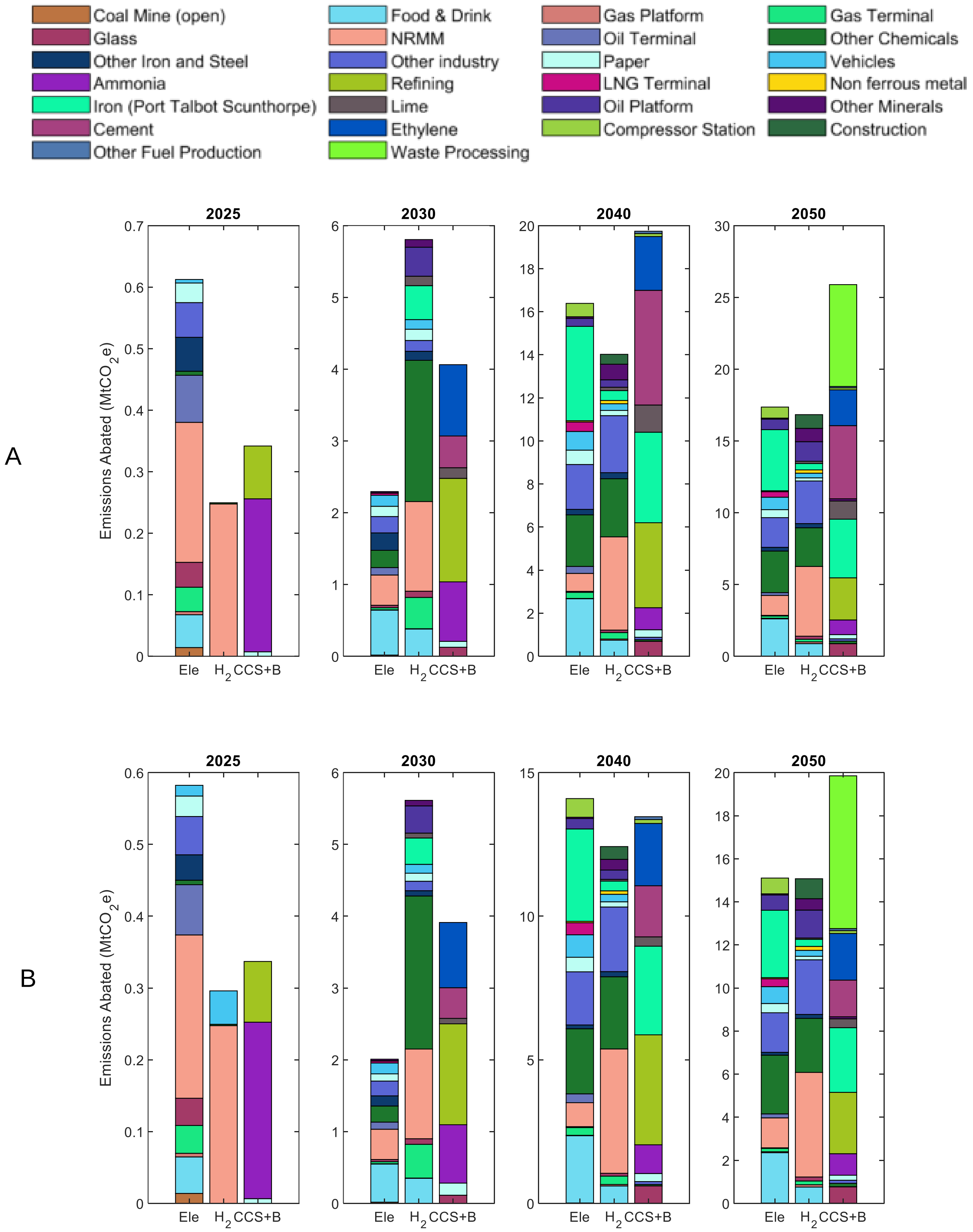


Figure A 3 Abated emissions for sectors by technology type per year- (A): Resource Efficiency 0%, (B): Resource Efficiency 150%



8.2 Discount rate

The results for the “3% and 15% discount rate” scenarios are presented in Figures A4-A5 respectively.

Figure A 4 Annual emissions for UK industry by technology type - (A): Discount rate 3%, (B): Discount rate 150%

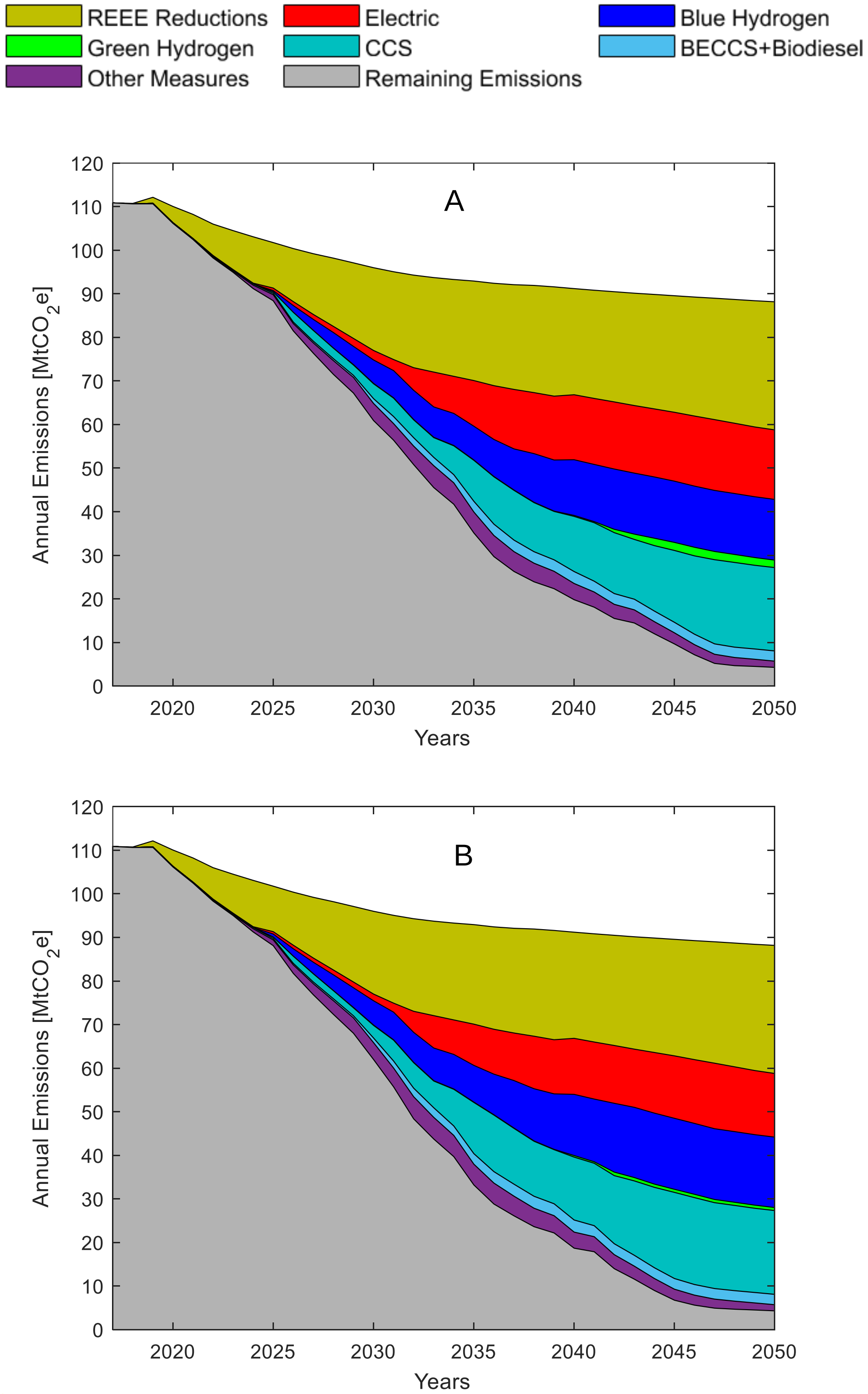
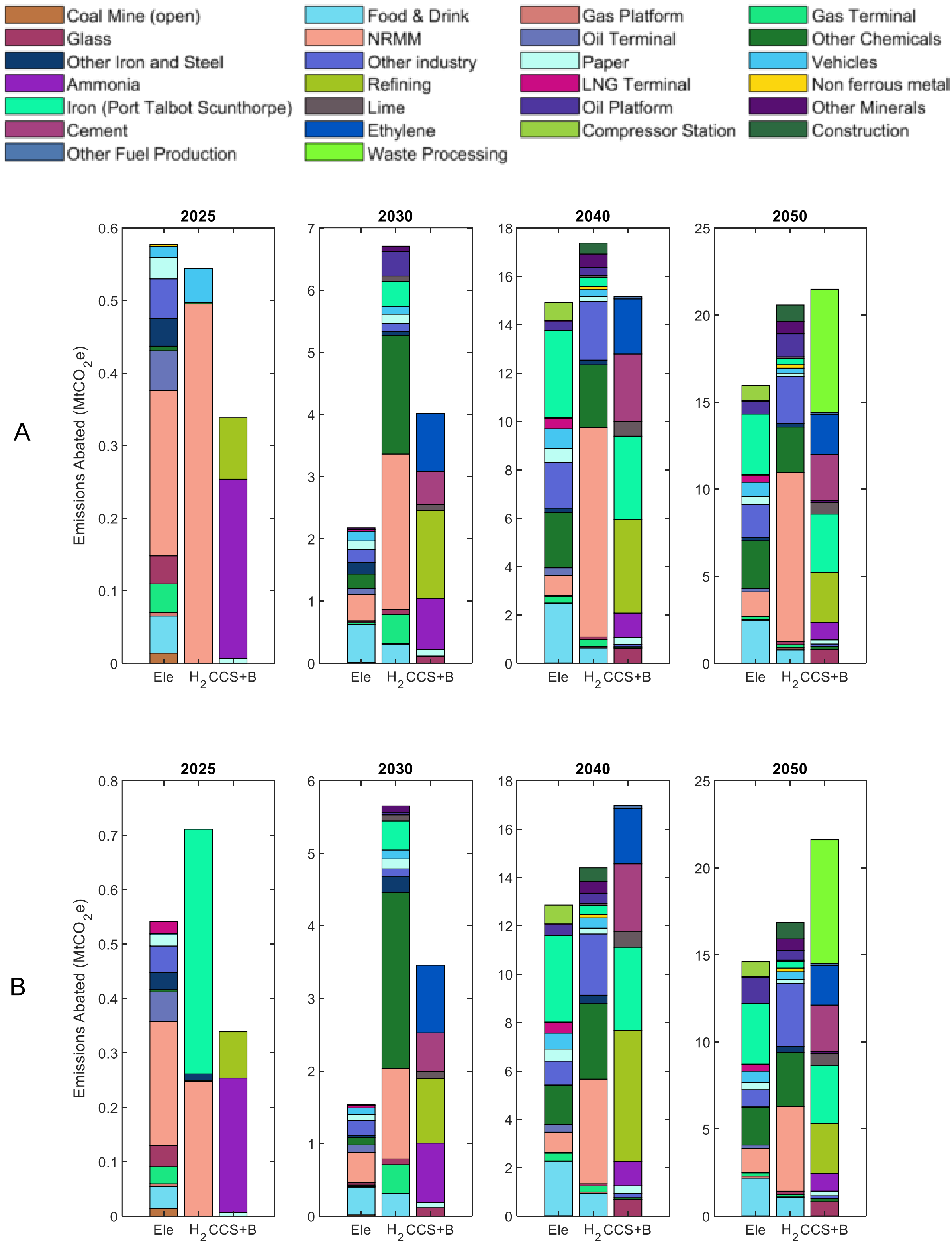


Figure A 5 Abated emissions for sectors by technology type per year- (A): Discount rate 3%, (B): Discount rate 15%



8.3 Carbon price

The results for the “£28/2050 and £546/2050” carbon price scenarios are presented in Figures A6-A9.

Figure A 6 Annual emissions for UK industry by technology type - (left): £28/2050 carbon price (right): £546/2050 carbon price

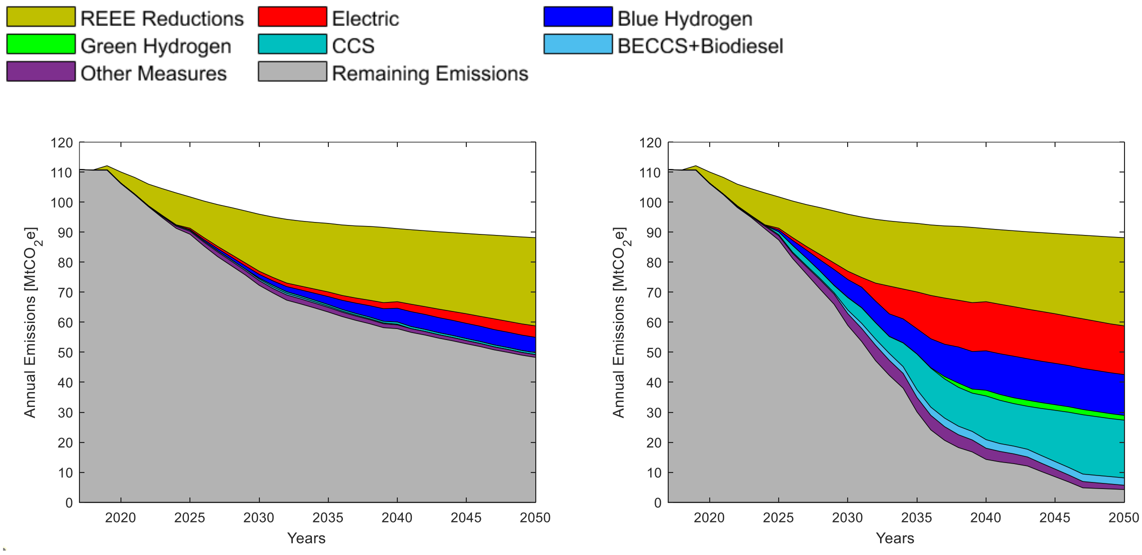


Figure A 7 Abatement measures annual net cost - (left): £28/2050 carbon price (right): £546/2050 carbon price

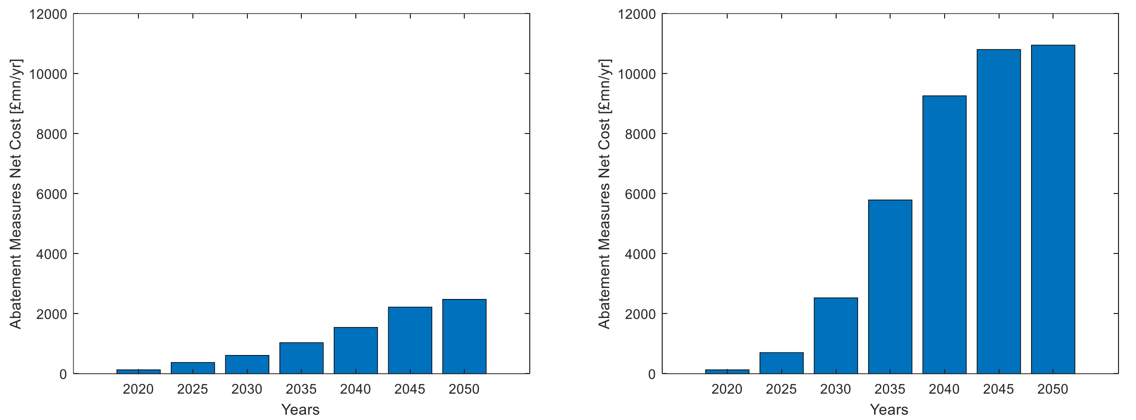


Figure A 8 Fuel consumption over years for UK industry- (A): £28/2050 carbon price (B): £546/2050 carbon price

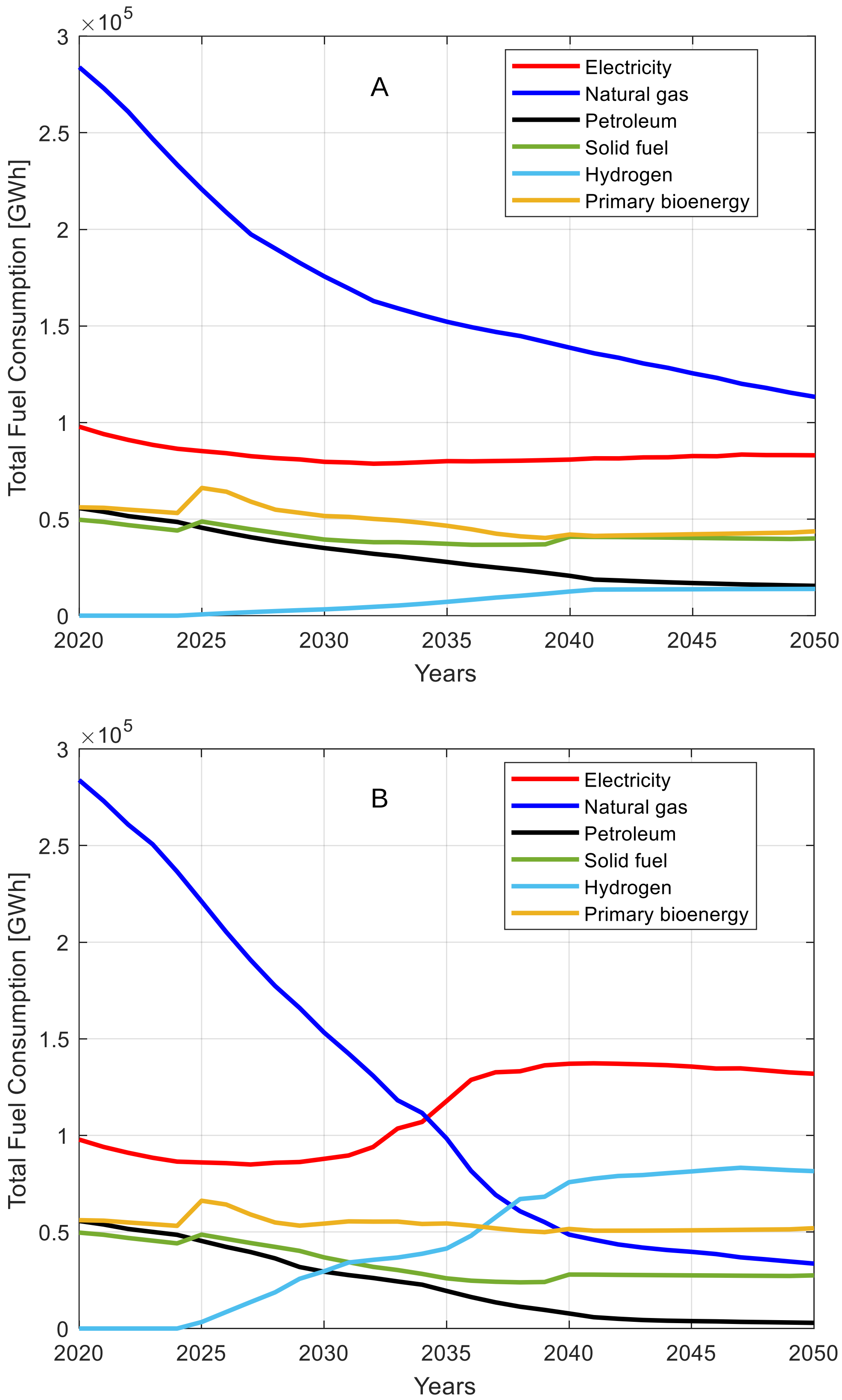
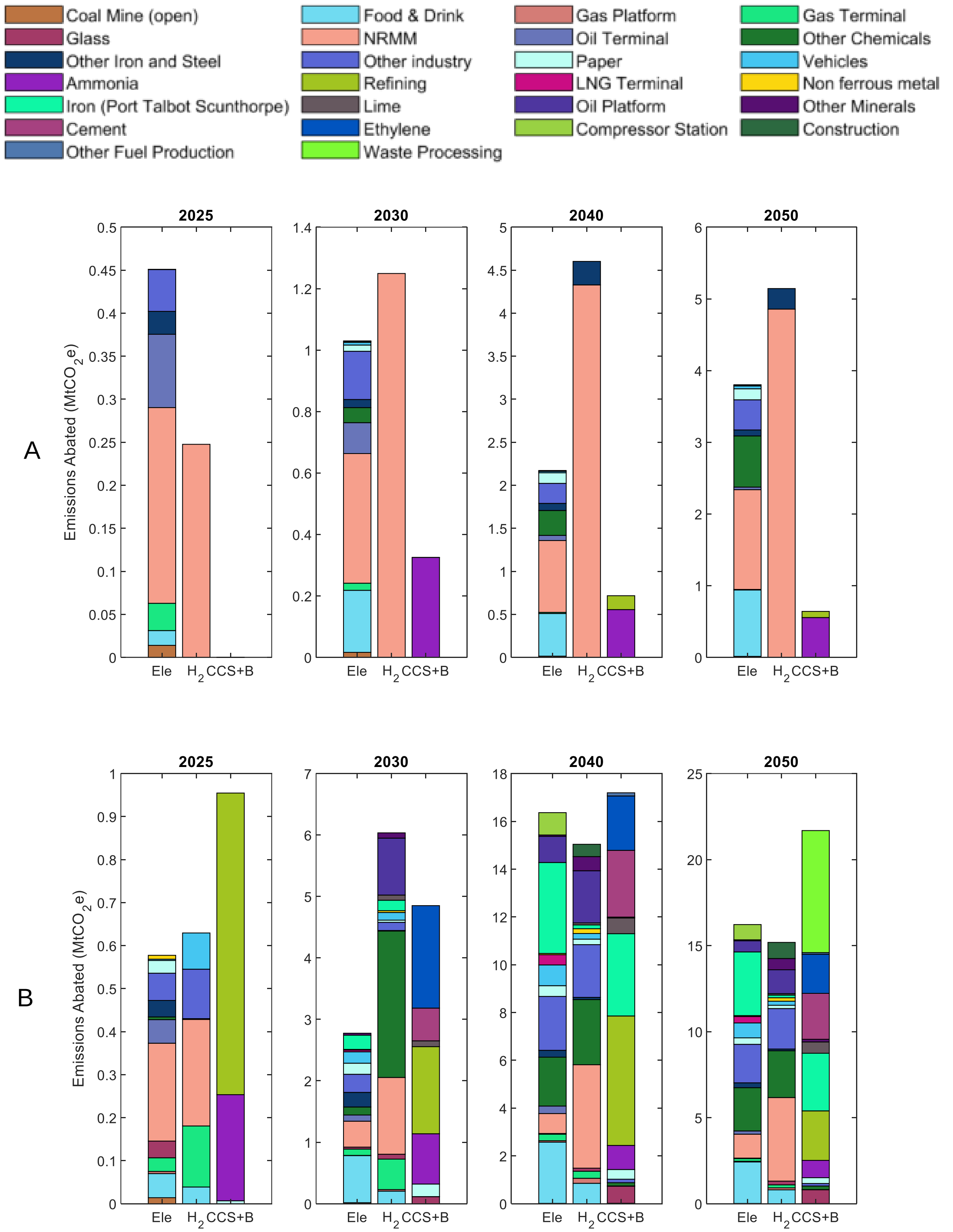


Figure A 9 Abated emissions for sectors by technology type per year- (A): £28/2050 carbon price (B): £546/2050 carbon price



8.4 Carbon capture and storage

The results for the £40/tCO_2 and £200/tCO_2” CO_2 T&S cost scenarios are presented in Figures A10-A11.

Figure A 10 Annual emissions for UK industry by technology type - (A): £40/tCO_2 CO2 T&S cost (B): £200/tCO_2 CO2 T&S cost

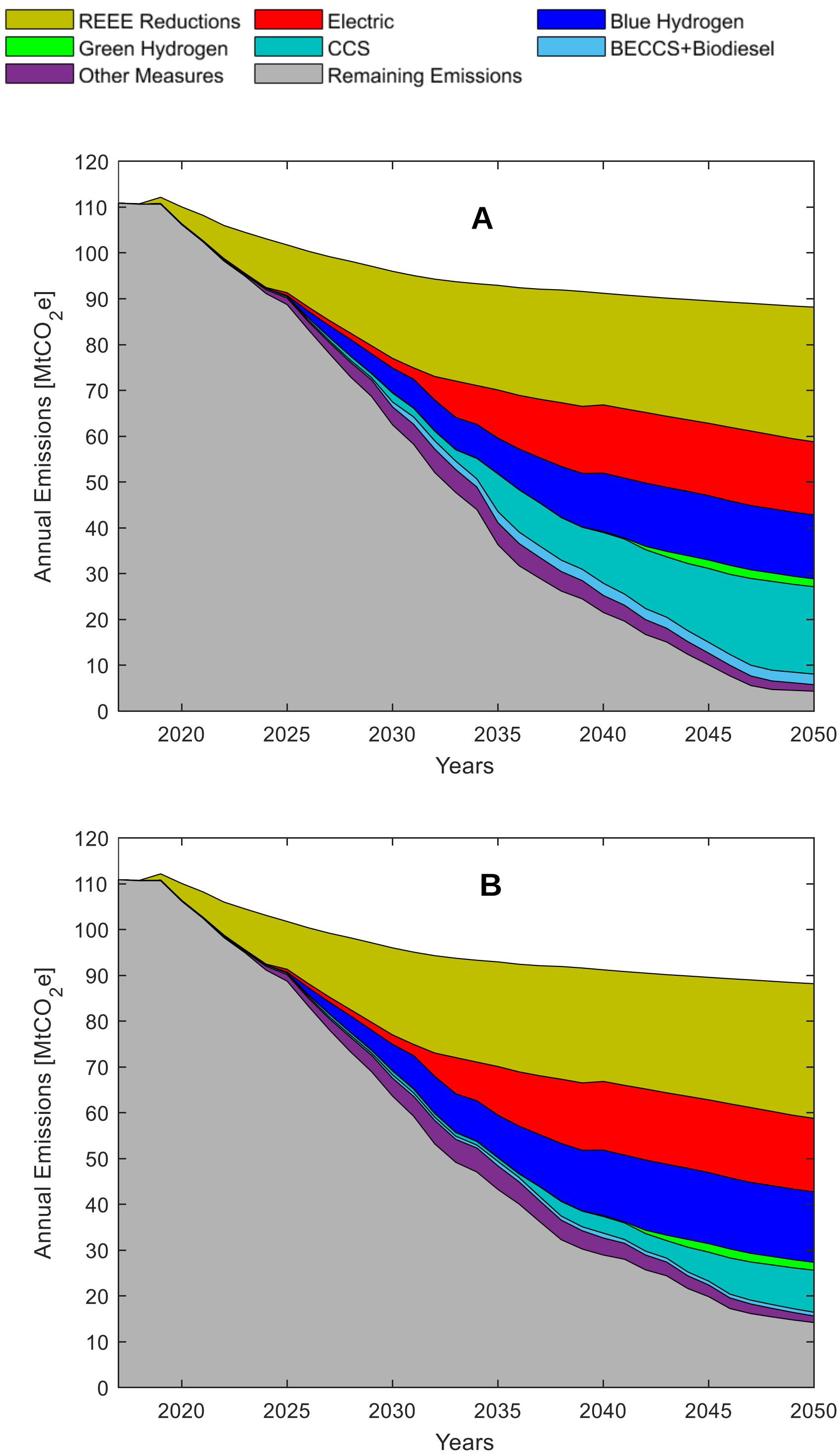
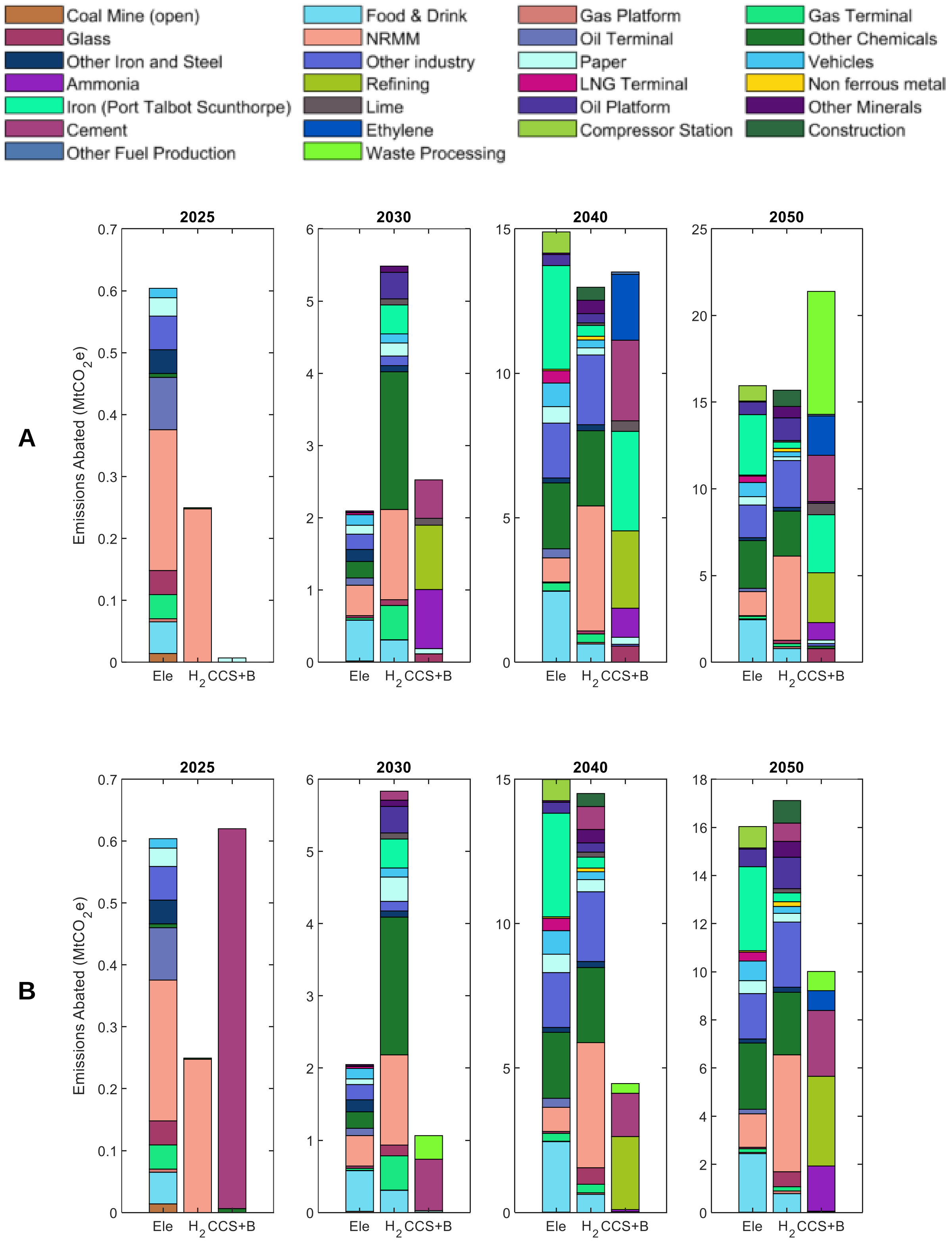


Figure A 11 Abated emissions for sectors by technology type per year- (A): £40/tCO₂ CO2 T&S cost (B): £200/tCO₂ CO2 T&S cost



8.5 Energy costs

The results for the "half and quadruple" fuel cost scenarios are presented in Figures A12-A15.

Figure A 12 Annual emissions for UK industry by technology type - (left): half fuel cost (right): quadruple fuel cost

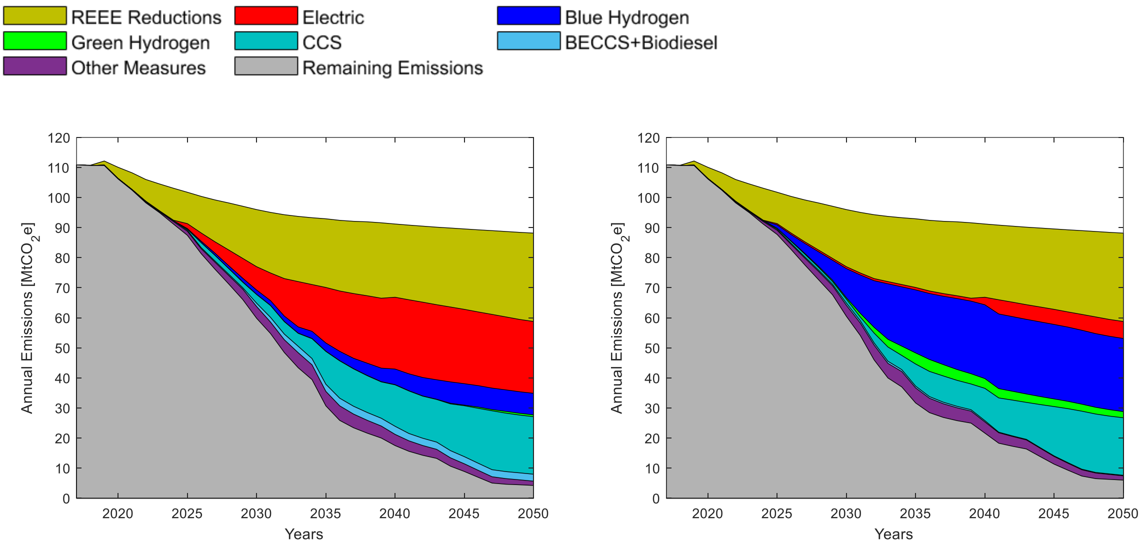


Figure A 13 Abatement measures annual net cost - (left): half fuel cost (right): quadruple fuel cost

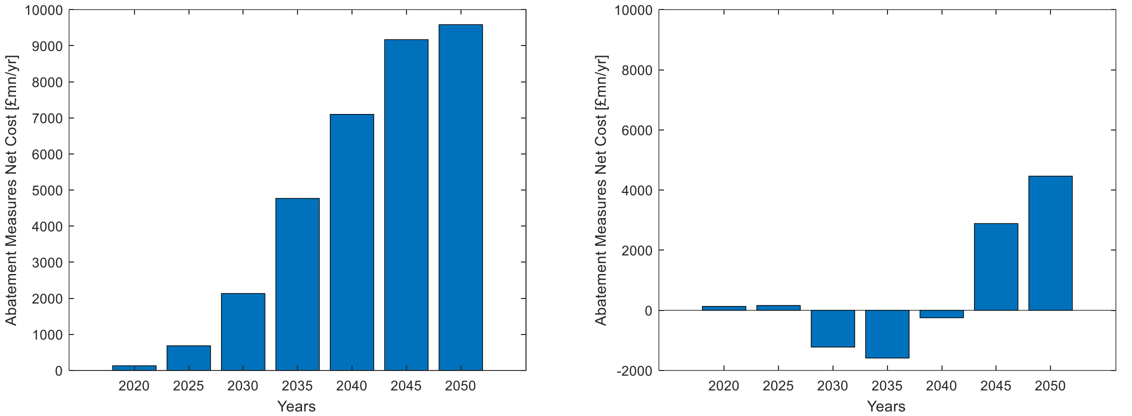
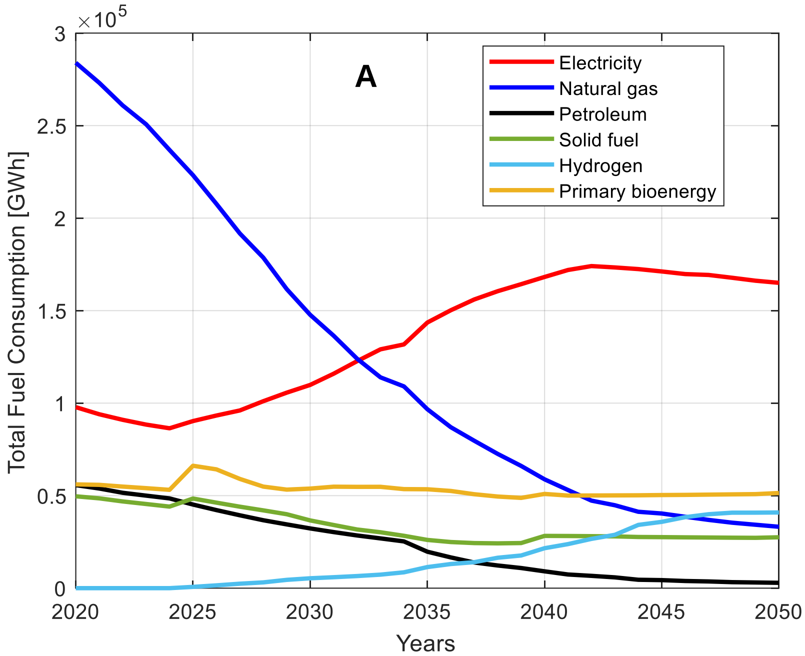


Figure A 14 Fuel consumption over years for UK industry- (A): half fuel cost price (B): quadruple fuel cost



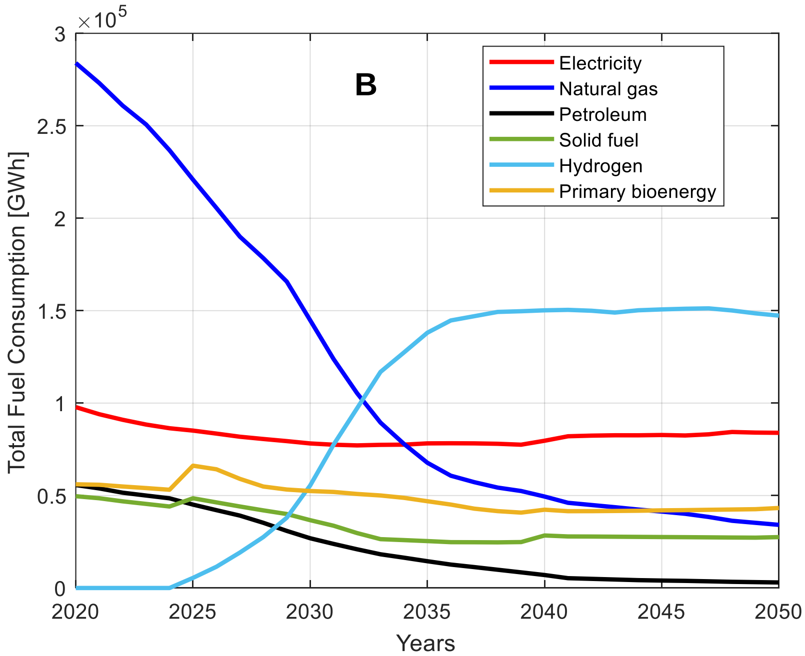
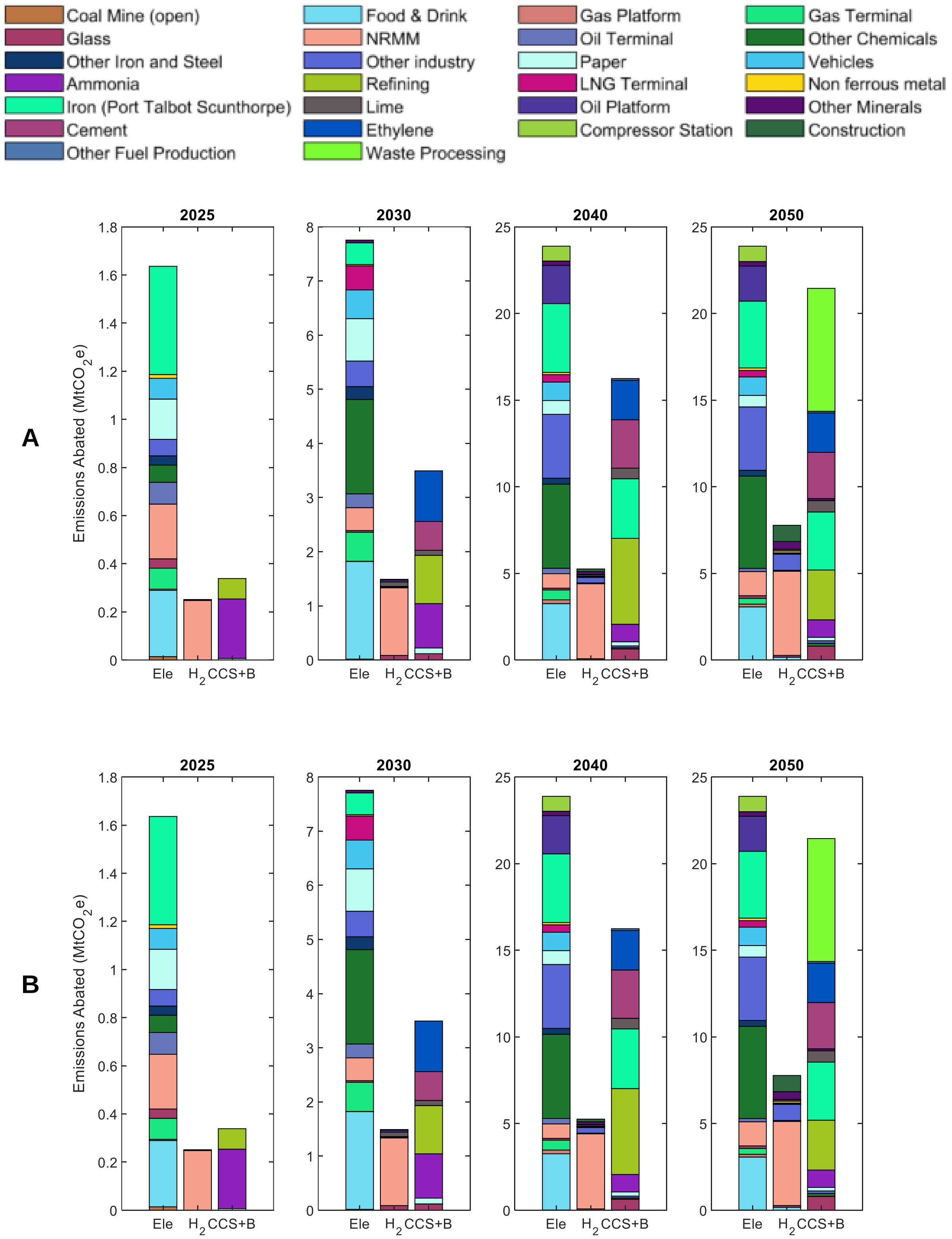


Figure A 15 Abated emissions for sectors by technology type per year- (A): half fuel cost (B): quadruple fuel cost



8.6 Hydrogen availability

The results for the “expensive hydrogen” and “Hydrogen production restricted in two clusters” scenarios are presented in Figures A16-A18.

Figure A 16 Annual emissions for UK industry by technology type - (left): “expensive hydrogen” (right): “Hydrogen production restricted in two clusters”

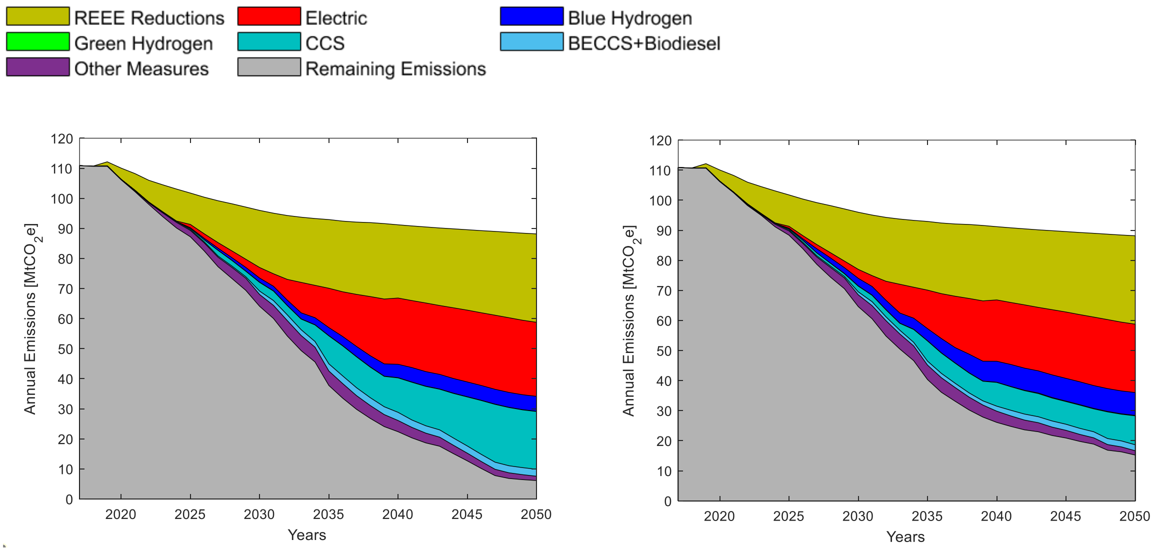


Figure A 17 Abatement measures annual net cost - (left): “expensive hydrogen” (right): “Hydrogen production restricted in two clusters”

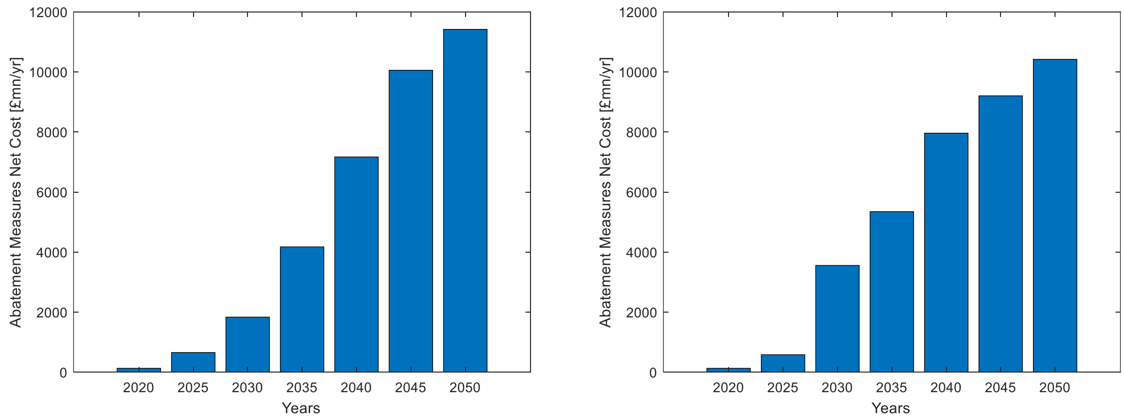
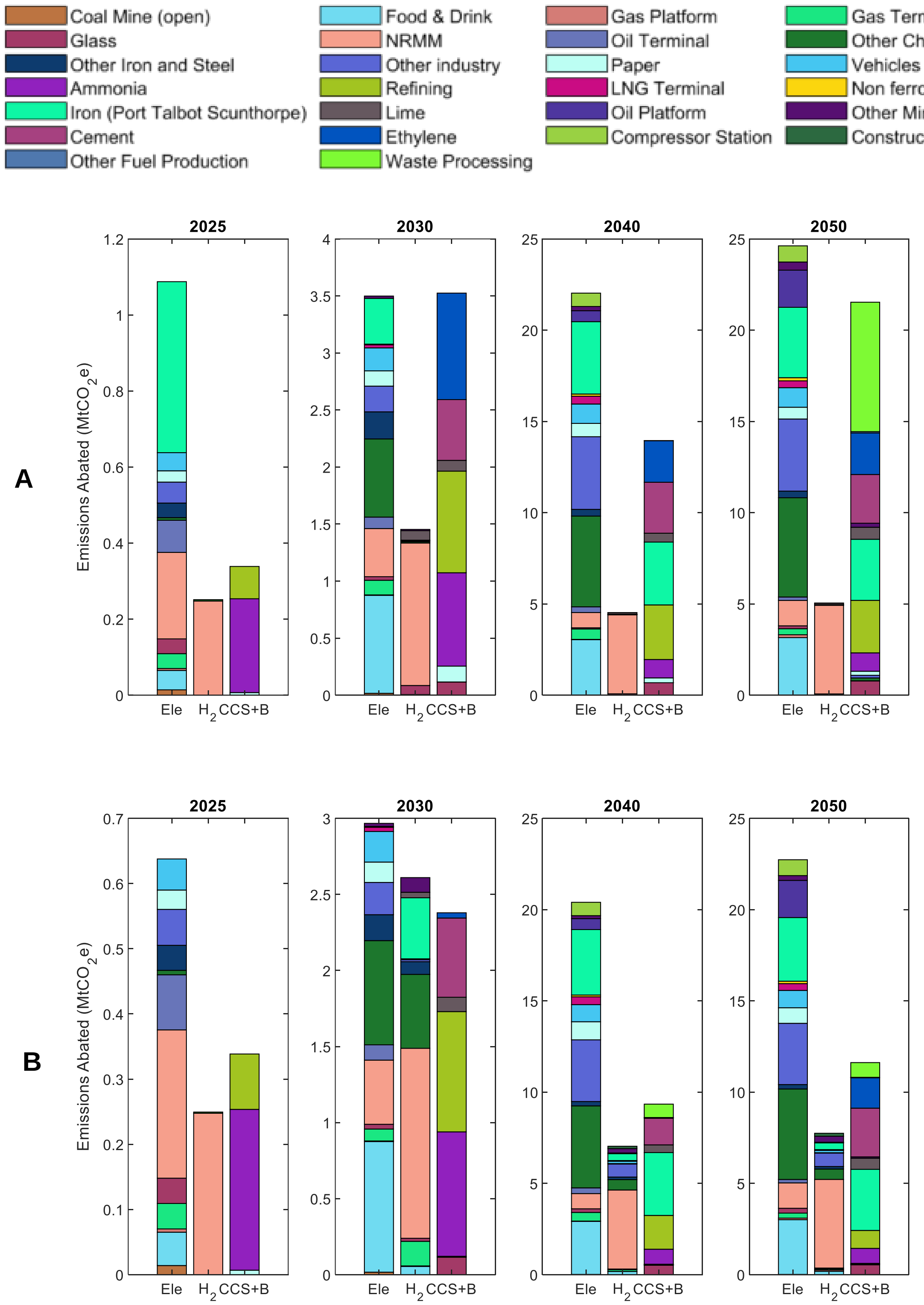


Figure A 18 Abated emissions for sectors by technology type per year- (A): “expensive hydrogen” (B): “Hydrogen production restricted in two clusters”



9. Appendix B: N-ZIP with no CO_2 storage

The N-ZIP model considers a wide range of factors and parameters in selecting abatement technologies. It appears to be effective in selecting the lowest NPV options subject to the constraints imposed upon it. However, because of the limited number of iterations it performs and the fact that the lowest NPV selection is performed as a separate step to the application of constraints, it can produce erroneous results if the availability of options with high NPV is significantly constrained.

This limitation is noted within the documentation but is worth highlighting given its potential significance to scenarios. Figure B1 and B2 illustrates the model's output when the CO_2 storage capacity is constrained to zero (i.e. constraining an option that would otherwise have a favourable NPV for many processes). We might expect a similar result to that achieved if the £200/t CO_2 T&S cost scenario examined in section 4.4 had no CCS at all; i.e. hydrogen and electrification being used as much as possible to abate emissions that CCS is no longer abating. In contrast, however, the results indicate very little hydrogen use and even less electrification. It appears that faced with this extreme constraint, the model does not manage to find a "next best" option that is actually possible. In practice, this exact issue is unlikely to be a problem; the modelled result only occurs in a rather extreme scenario. All models exhibit problems when used well outside of their designed operating "conditions" and this is no exception. However, the potential issue is highlighted here as it illustrates that there may be subtler but related issues if more limited (e.g. localised) but still extreme constraints are used in order to investigate a specific question.

Figure B 1: N-ZIP modelled output when CO_2 storage capacity is set to zero

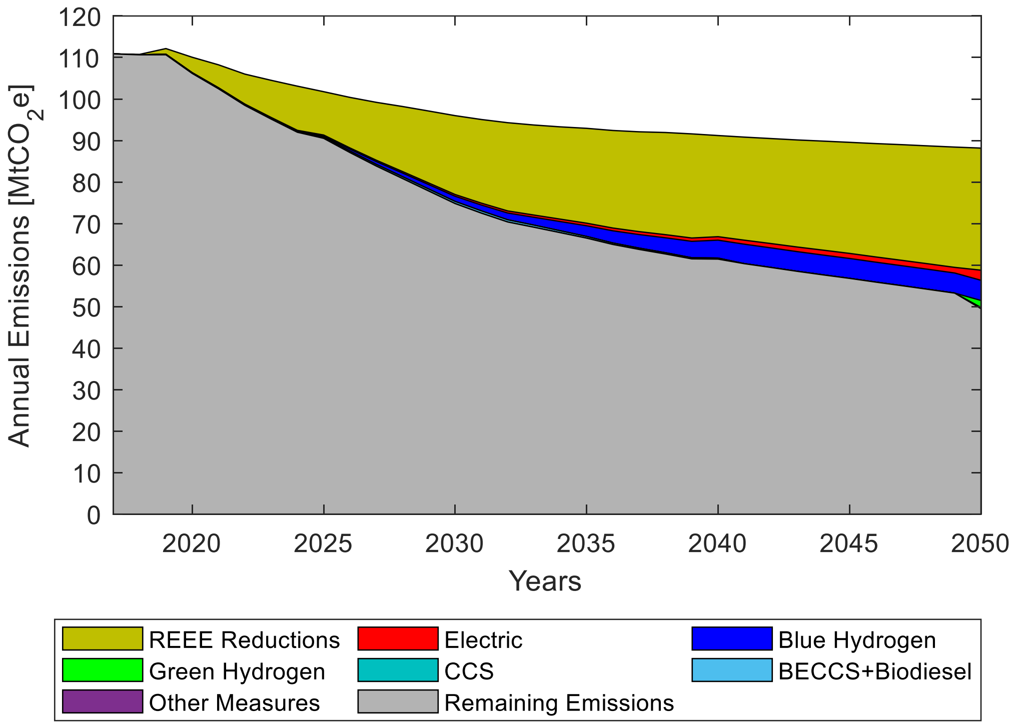


Figure B 2: Abated emissions for sectors by technology type per year when CO_2 storage capacity is set to zero