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Meeting the costs of decarbonising industry – The potential effects on prices and competitiveness (a case study of the UK)

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ABSTRACT

Industry produces a third of global greenhouse gas emissions and needs to be decarbonised as countries strive for net zero. But how might the costs of this be met and what effect might the options have on businesses and consumers? Using the UK as a case study, we investigate the relative effect on prices and profit margins of three idealised illustrative scenarios for distributing the costs of decarbonising industry: (1) absorbing them, (2) passing them on to consumers, and (3) sharing them along the relevant value chains. To do this, we combine direct process cost projections from a detailed industry pathway model (covering 115 sector-process combinations and 96 unique low-carbon technologies) with techniques exploiting multi-regional input-output analysis. Industrial decarbonisation consistent with net-zero goals can be achieved with an aggregate increase in prices as low as 0.8%, and minimal impact on equality. However, the impact on some industries is more pronounced; while costs might be beneficially shared between sectors to some extent, some will find this more challenging. The findings are relevant to industrial decarbonisation policies and the support they need to provide, the effects that industrial decarbonisation might have on equality, and its potential effect on international competition.

1. Introduction

Industry currently accounts for around a third of global greenhouse gas (GHG) emissions, and a quarter of those occurring in the UK (BEIS, 2022). Eliminating most of these emissions is critical to mitigating climate change. Various options are available to achieve this; these can be largely characterised as resource efficiency and energy efficiency (REEE) options, fuel switching options (e.g. to low carbon electricity, hydrogen or bioenergy), process switching, and carbon capture and utilisation or storage (CCUS) (Cooper and Hammond, 2018; Element Energy, 2020).

Many of these options are cost-effective (if the cost of emissions is included) but are likely to present additional costs to implement. The way in which these costs are met will affect their economic viability and broader impacts; issues that are considered key to their overall political acceptability (Busch et al., 2018; HM Government, 2021a).

If decarbonisation costs are passed on then they will affect the prices paid by consumers. Stede et al. (2021) recently investigated the effect that carbon costs (i.e. a cost applied to GHG emissions) might have on prices if fully passed through to consumers. They found that if a relatively modest carbon price (€30/tonne) is fully passed through, it could result in average supply chain costs that are 1.3% of gross valued added (GVA) for final product costs, and 23% of GVA for basic materials. Passing these costs on to consumers would result in price increases (in Germany) of less than 0.2%. In contrast to the present study, they considered carbon prices applied to emissions rather than the actual cost of abating these emissions (which may be less) and considered emissions within the scope of the EU Emissions Trading Scheme (ETS) in order to provide relevance to discussions around its development. However, their study demonstrates that there are important variations in the effect that emissions reduction may have on the economics of different sectors that merit further exploration.

It is possible for the adoption of low-carbon technologies to exacerbate inequality if they result in the prices of product groups changing by unequal amounts (Hardadi et al., 2021). For example, they would be regressive if there are greater relative price increases for the products that form a greater fraction of low-income household expenditure. Owen and Barrett (2020) found that this is the case for current UK policies that largely relate to energy (e.g. they currently add 13% to energy bills that are 10% of expenditure for lowest-income, but only 1.5% of expenditure for highest-income households). As a result, they recommend that general taxation is a more equitable approach for funding those measures. It

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is important to consider whether measures to decarbonise industry will exhibit similar characteristics, or whether the distribution of costs to prices is more equitable.

Price changes may affect the competitiveness of products (Turner et al., 2023). To ensure that decarbonisation is effective, it is important that policies are designed to ensure that these price changes do not result in production shifting to regions or processes with greater emissions (Sturge, 2020). Grubb et al. (2022) investigated the historical incidence of this and found that carbon leakage is currently small (emissions transfers peaked in 2006) but that this is due to the shielding of key industrial sectors which is incompatible with incentivising deeper decarbonisation. In fact, global trade has the potential to maximise efficiencies in decarbonisation of industry if given appropriate direction by policy (Jakob et al., 2022). Analysis of the related changes in future prices that might occur is important in facilitating this policy design.

Carbon border adjustments have been suggested as an approach to achieve a level playing field without compromising domestic schemes (Sakai and Barrett, 2016). Despite various challenges relating to world trade organisation (WTO) rules (Böhringer et al., 2022; Mehling et al., 2019), the EU is now in the process of implementing a scheme (European Commission, 2021; European Council, 2022). However, in considering the effect of such schemes, it is relevant to consider the impact on prices of not only the effective carbon costs but also the cost of the low-carbon technologies that might be adopted as a result. It is also important to consider the ways in which these costs might be distributed between products, and between the various actors involved.

To address these research needs, this paper presents an assessment of the relative changes in prices or margins that could occur if these costs are met in three illustrative scenarios. These are: the costs met by the industrial sectors abating them, the costs met by consumers (through increases in prices), and the costs met by the supply chain that gains value from the processes. The paper does not assess the full economic effects of the costs. Rather, it aims to identify where there might be pressure-points or problems if the costs are met in these ways and therefore indicate aspects of this transition that might require more specific policy.

2. Methodology

2.1. Overview, scope and limitations

The overall approach used was to take estimations of costs from an existing industrial decarbonisation model and then create three illustrative scenarios to assess the effect on margins and prices that might occur if these costs were met in different ways. The UK was used as a case-study to explore the potential impacts. The industrial decarbonisation model used was the Net-Zero Industrial Pathways (N-ZIP) model (Element Energy, 2020). N-ZIP is freely available as an Excel spreadsheet and described below (section 2.2); it currently relates to UK industrial decarbonisation. The three illustrative scenarios are.

1. "Take the hit". Emitting industries absorb the cost of adopting low-carbon technologies as a reduction in their profits.
2. "Pass it on". The costs are perfectly passed on to final consumers (via the entire supply chain)
3. "Spread it out". The costs are partially passed on, such that they are spread across the whole supply chain for each final product; this causes reductions in profits that are proportional to those profits.

These scenarios are described in sections 2.3, 2.4 and 2.5 along with the methods used to assess them. The illustrative scenarios are not intended to be predictions or targets; rather, they are to illustrate the effects if all of the costs were met by one group of notional stakeholders (i.e. producers, consumers, or supply chain respectively). In reality we would expect a combination of these to meet the costs (see Fig. 1). The way in which the costs are actually met (and therefore the combination of these effects that occurs) would depend upon a broad range of factors. These include considerations such as policy, the judgements and priorities of individual businesses, broader economic conditions, and international competition; the effect of these factors is outside the scope of this analysis.

Fig. 1. The scenarios are idealised illustrations, some aspects of each may emerge.

The costs (and financing of costs) that industry faces could be completely changed if they are to some extent socialised. That is, a policy regime (in particular, taxes and subsidies) could completely change the nature of the remaining costs to industry that then get distributed. This aspect is not considered in this analysis as it depends entirely upon the policy mechanisms in place (in principle, all of the costs could be socialised) but this should not be interpreted as an indication that the socialisation of costs will not have a significant effect. Rather, the results should be interpreted as a range of effects if the low-carbon technologies are invested in, but the costs met without government funding or subsidies. They are presented with the carbon-cost of residual emissions separated out where appropriate (see section 2.2, below) so that this can be considered separately if relevant to a given policy application. The results therefore have relevance to policy in considering where these funding or subsidy interventions might be necessary.

The activities (and therefore emissions and costs) that N-ZIP incorporates is a subset of that occurring in the UK (see Fig. 2). It does not include other parts of the economy (i.e. transport, buildings, power generation, other commercial activities, or agriculture, forestry and land-use). Nor does it include "non-industrial" activity within the industrial sectors. For example, transport or building services that are used by industrial sectors are excluded; these are significant for sectors such as construction and utilities (which includes waste services), but less so for others. N-ZIP is based on a territorial perspective (i.e. consistent with national emissions inventories and UNFCCC reporting) rather than a residential perspective (i.e. as used in national accounts). This results in relatively small differences for the industrial sector (e.g. N-ZIP's territorial perspective includes any emissions in the UK due to the activity of foreign-owned industry, but excludes emissions overseas even if due to the activity of UK owned industry). It is this subset of emissions (roughly one-sixth of UK GHG emissions) and costs that is reflected in the present analysis of effects.

The analysis for the "pass it on" and "spread it out" illustrative scenarios is based on historic inter-industry structure data for 2019. This is explored in section 2.4 (below), but it should be noted that it means that elasticity and substitution effects are not included in these scenarios.

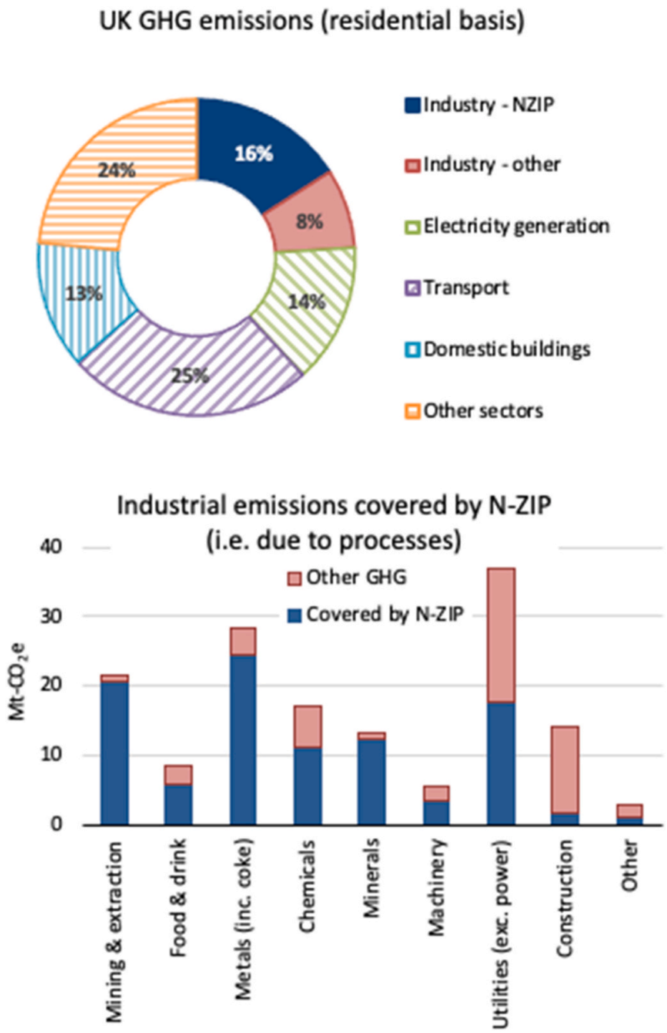

Fig. 2. GHG emissions within scope of N-ZIP model (i.e. territorial industrial processes) compared to total UK emissions (residential basis, 2017).

2.2. Cost projections from the Net-Zero Industrial Pathways (N-ZIP) model

The costs and emissions projections used as inputs into this analysis were taken from runs of the N-ZIP model. N-ZIP generates both a "baseline" projection of annualised costs and emissions (for each year, and industrial process at each site), and a "decarbonisation" projection in which a carbon price is applied and low-carbon process technologies are available. This analysis took both projections ("baseline" and "decarbonisation"), and distributed the industrial process costs according to each of the three rationales in turn. The differences in the results (between those when the baseline and the decarbonisation projected costs were used as inputs) were interpreted to represent the impact of adopting the low-carbon technologies.

The projections from N-ZIP include the effect of changes in the baseline emitting activity of sectors (e.g. physical quantity of steel produced); by default the projected physical output decreases (in line with government projections) and so the "baseline" emissions decrease due to reduced activity (even before efficiency or low-carbon technologies are taken account of). For the present analysis, the results (costs and emissions) from N-ZIP were adjusted in order to be relative to constant physical output from 2020. This means that they reflect price and emissions changes that relate to a fixed physical output rather than conflating changes due to adopting low-carbon technologies with improvements in productivity. The technology cost projections it provides are expressed as real 2020 GB P (rather than nominal, i.e. they do not vary with inflation).

N-ZIP was developed by Element Energy and used to inform the sixth carbon budget advice from the UK's Climate Change Committee (CCC, 2020). It is described in detail in its documentation (Element Energy & Jacobs, 2018; Element Energy, 2019, 2020) and is freely available in the format of an Excel spreadsheet. Gailani et al. (2021) examined the sensitivity of the results from N-ZIP to different input assumptions and found it to perform robustly with a reasonable range of alternative assumptions. In this section, we provide an overview of its functionality and the adjustments we made for its output to be suitable for this analysis.

N-ZIP is a bottom-up model that selects the decarbonisation options with the best Net-Present Value (NPV) for industrial sites across the United Kingdom (UK). It takes a societal perspective with perfect foresight (in the default settings used for this study). For this work, the set of parameters relating to the CCC's "Balanced Net Zero scenario" were used for the main set of analysis, with variations explained in the section on sensitivity analysis (section 2.6, below).

As a starting point, N-ZIP takes projections for industrial activity and the GHG emissions due to them. These projections are disaggregated by industrial sector, the site at which they occur (large point sites are included individually, whilst smaller emitters are treated as "pseudo-sites" that represent distributions over geographic regions), and the process that drives them (e.g. provision of high-temperature heat).

For each of these processes (at each site or set of sites), N-ZIP calculates the NPV of adopting each appropriate low-emissions technology in each year up to 2050. Various low-emissions technologies are characterised as suitable for each process. These NPV calculations include.

- Capital expenditure (capex) on technologies,
- Fixed operational expenditure (opex),
- Variable expenditure on energy, hydrogen infrastructure, and on CO_2 transport and storage,
- A carbon price relating to GHG emissions.

The calculations are subject to constraints on hydrogen availability, and on CO_2 transport and storage infrastructure availability (each specific for each location and year). However, there are no constraints modelled for new or upgraded connections to the electricity network. Technology availability, deployment rates and lifespan are also taken into account.

Within the N-ZIP model, the "baseline" projections of annual activity (and GHG emissions) are based on estimates from the CCC that draw on historical data on energy (from the Digest of UK Energy Statistics), greenhouse gas emissions (from the 2017 National Atmospheric Emissions Inventory) and energy and emissions projections produced by the UK Government. These projections are adjusted to account for potential resource efficiency and energy efficiency (REEE) measures. The projections run from the present, through to beyond 2050 (such that the NPV for adopting technologies to 2050 can be calculated, taking account of equipment lifetimes extending beyond it).

The low-emissions technology options typically represent a net cost compared to the default ("counterfactual") technology options if the carbon price is excluded, but a net saving if it is included (hence their adoption within the model). Within the model, the assumed carbon price follows a projected trajectory. In the "Balanced scenario" used here, the carbon price trajectory is based upon the UK Treasury's "Green Book" supplementary guidance's "high untraded projection" (BEIS, 2019); reaching a carbon price of £346/t in 2050 (see Fig. 3). The inclusion of a carbon price is an important factor in ensuring that the low-carbon technologies have a better NPV than the conventional alternative but there are different ways in which it might be applied.

Some "residual" GHG emissions will still occur even after low-carbon technologies are applied and it is possible that these will be subject to the carbon price. Within the analysis presented here, the distribution of

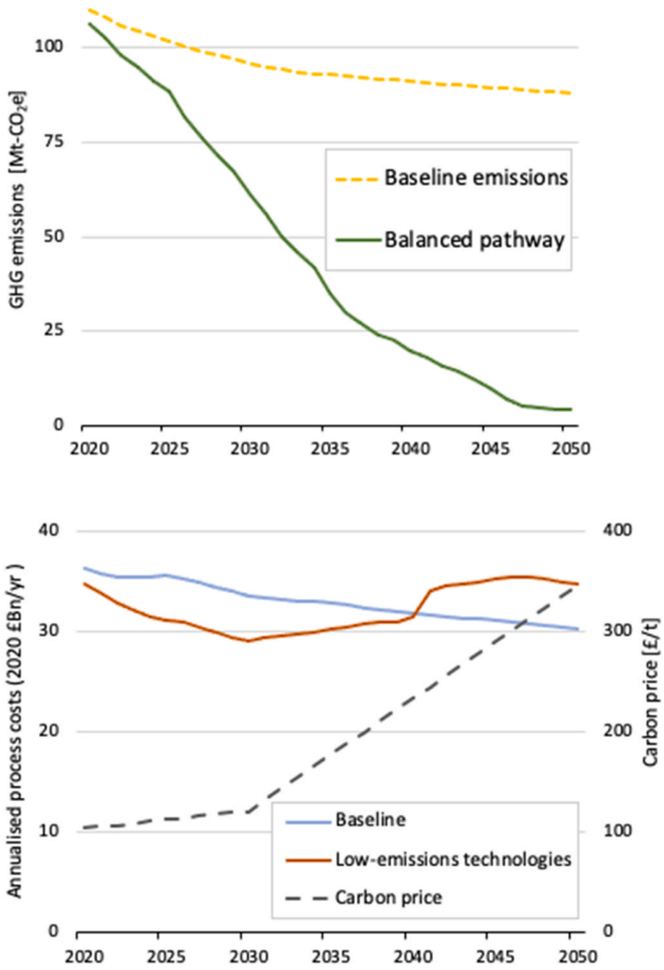

Fig. 3. Industrial emissions, process costs and carbon price in "Balanced scenario" modelled by N-ZIP.

this cost (i.e. the carbon cost of residual emissions) is considered separately to the direct costs due to adopting the low-carbon technologies. It is worthwhile to compare their relative potential magnitudes but it should be noted that they may be applied in different ways that have different effects. For example, the direct cost of replacing one technology with a low-carbon alternative might be met by a business and form part of their investment planning; conversely, the application of a carbon price to their residual emissions might take the form of a variety of policy instruments that the business has less direct influence over.

Cost and emissions projections from the N-ZIP model were taken and distributed according to different rationales (see sections 2.3, 2.4 and 2.5 below). To facilitate this, the site level results from N-ZIP were aggregated to sectors. This was done by creating a concordance table to map the sector descriptions in N-ZIP to the SIC codes used in the national accounts. In the few instances where these mappings reflect many-to-many relationships (e.g. petrochemicals), the proportions were weighted based on the respective emissions intensities. The various site-level impacts were then extracted from the N-ZIP results and assigned to the relevant sectors. The included impacts were: the costs for the low-carbon technologies (consisting of annualised capex, opex, and infrastructure costs relating to hydrogen provision and CO_2 sequestration), the costs of the "counterfactual" technologies (i.e. those that would be used if the low-carbon technologies aren't adopted; providing a baseline), the residual GHG emissions (i.e. those that remain after the low-carbon technologies are applied) and the baseline GHG emissions (i.e. those that would occur if the sites continued to use their counterfactual/baseline technologies). These impacts were extracted for the time-period from 2020 through to 2050.

2.3. *Illustrative scenario 1: "take the hit"*

In the "Take the hit" illustrative scenario, the costs are assumed to be absorbed by the industry that adopts the low-carbon technologies. This scenario would be consistent with a world in which there is little scope to increase the prices that companies ask for their products; for example, if they wish to maintain a given market share but demand for their product is sensitive to price (perhaps due to highly elastic demand, products that can be readily substituted, or competitors who do not need to pay for low-carbon processes). Or a world in which other factors motivate or enable companies to bear much of the upfront cost of the technologies. The results have policy relevance in illustrating the magnitude of the costs relative to the profits that the businesses make and therefore the extent to which these costs might be a challenge for them.

To provide context, the costs are expressed relative to the average profit within each sector. This profit is defined here as gross operating surplus and is taken from national accounts (HM Government, 2022). The sectoral gross operating surplus that is used is from 2019 (chosen to exclude abnormalities due to Covid-19 pandemic). This is done consistently for results relating to the future (e.g. 2030, 2040 and 2050). Various projections for growth in surpluses are available but using these risks conflating changes in the costs (numerator) with changes in the surplus (denominator) that are subject to a different set of uncertainties. If the surplus of a sector does increase, this would reduce the cost of the technologies relative to it.

Combined with the adjustments to the N-ZIP results noted above and the fact that the costs from N-ZIP are expressed as real values, this means that the costs presented are those that would be incurred if physical output remains constant, relative to 2020 gross surplus. That is, the variations in the costs reflect the evolution of the costs of the technologies and their adoption rather than changes in physical output, profit margin, or inflation.

2.4. *Illustrative scenario 2: "pass it on"*

In the "Pass it on" illustrative scenario, the costs are entirely passed on to final consumers (households, public spending, and capital formation) via the supply chain. That is, a company facing costs to adopt low-carbon processes, increases the price of its products to cover this cost. In turn, the companies buying these products increase their prices to reflect this price increase, and also to reflect any additional direct process cost increases they might face. These costs and resulting price increases cascade through the supply chain, resulting in price increases for final consumers. If companies switching to low-carbon production can pass on the costs in this way, then their profit margins will not be directly affected. This illustrative scenario would reflect a world in which the demand is fixed and all companies can increase their prices in the same manner as each other.

The results from this scenario have relevance to the potential effect on consumers as they represent the increase in the average prices that they might pay. The results are therefore aggregated across the types of products. They are alternatively aggregated across the typical "basket" of goods bought by consumers to show the overall effects on household spending. Furthermore, the average "basket" of goods for different income groups (differentiated by household income deciles) is used to investigate whether this overall effect might vary by income group; this is relevant to considerations around whether the costs might have implications for equality (Owen and Barrett, 2020).

The results from this scenario are also relevant to effects on the potential competitiveness of sectors implementing these decarbonisation options. A worst-case consideration would be that an industrial sector needs to increase its prices to fully reflect the additional costs of low-carbon processes and the carbon costs of its residual emissions, whereas a competing industrial sector (i.e. from overseas) does not face a carbon price and also does not adopt low-carbon processes. These results are therefore disaggregated with carbon costs and process costs given separately.

To calculate the price increases that would be necessary under this scenario, we used input-output analysis (IOA). IOA was used to calculate the "embodied cost increase" in an equivalent manner to that used elsewhere to calculate the embodied GHG or other embodied impacts associated with consumption of goods and services by final users (e.g. Barrett et al., 2013; Tukker et al., 2020; Wood et al., 2019). This approach (detailed below) provides equivalent results to the cost-push Leontief model (Miller and Blair, 2009), or the Ghosh price model (this equivalence is explained and demonstrated by Dietzenbacher (1989, 1997)).

In general, IOA assesses the overall (whole supply chain) activity across the economy that is driven by the consumption of particular goods and services. These supply chain relationships can then be expanded upon to allocate the impacts of those activities to the final demands that drive them. To calculate the total supply chain relationships, IOA uses data on inter-industry transactions. This data is typically arranged as either Input-Output tables (IOTs) or Supply-Use tables (SUTs), with ancillary extension tables providing data on the corresponding direct impacts due to the activity in each sector. Related tables detail the final consumption of goods and services that drive the activity and inter-industry transaction, enabling the total embodied activity (and therefore embodied impacts) associated with each component of final consumption to be calculated.

The input-output tables used in this study were the UK multi-regional IOT (UK-MRIOT) for 2019. These have global coverage but focus on the UK. They are used to calculate the UK consumption-basis GHG emissions footprint (HM Government, 2021b). The tables use 112 sector definitions, consistent with UK Office of National Statistics (ONS) data and so the results can be compared on a consistent basis with other national statistics and environmental accounts. Data is included for the UK, plus 14 other regions covering the rest of the world. The methods used to construct the UK-MRIOT are documented (HM Government, 2021a). The majority of the underlying data to create it were taken from the well-received Exiobase MRIOT (Stadler et al., 2018) and the UK Supply-Use Tables (HM Government, 2022). UK-MRIOT has been used in academic literature, for example (Owen and Barrett, 2020) and (in a previous format) by (Barrett et al., 2013). UK-MRIOT data for 2019 was used (rather than for a more recent year) in order to avoid any abnormalities due to the Covid-19 pandemic.

The process used to calculate the results for this scenario was:

$$G = (E/x).L.U$$

Where G is an $l \times n$ vector of the l proportional impacts (e.g. price increase) associated with/embodied in the n consumption patterns described by U. U is an $m \times n$ vector giving the n consumption patterns of groups of products that are of interest (similar to Y, i.e. final consumption, when calculating a consumption-based footprint). L is the $m\times m$ total requirements ("Leontief") matrix that gives the total dependence of each of m products on m product inputs (note that for illustration here we adopt the convention of defining each product as the output of a particular sector). (E/x) is an $l \times m$ matrix of the direct impact intensities for each of the m sectors; that is, the l direct impacts of each sector divided by its total output.

Impacts were assessed for different groups of products (i.e. columns of U in the equation above). These groups were based on either aggregations of types of products (e.g. "Food" encompassing various different types of food product) or the mix that is typical for a group of consumers (such as those within first decile of household incomes). Where impacts were assessed in relation to the types of products, each consumption vector was constructed by including the total consumption (for households and government) of the relevant products, such that the results for a product group are weighted by the relative consumption of the products it consists of. Where impacts were assessed in relation to different consumer groups, the consumption vectors were created to represent spending patterns disaggregated by household income deciles. Data for these patterns was derived from (Owen and Barrett, 2020) and described in more detail there. Each column in U was then normalised to a total of one (such that their elements are proportions of the total rather than absolute quantities).

For the present study, the direct impact intensities matrix (E/x) was populated using outputs aggregated from N-ZIP as described at the end of section 2.2 (above). These impacts relate to the reduction of emissions from UK industry. Distributing the costs of industrial decarbonisation in regions outside the UK is not the primary objective of this study, but given the importance of international supply chains, it is appropriate to provide some context relating to these. That is, the equivalent price increases in the UK that might be incurred as a result of the costs of decarbonising industry outside the UK. Therefore, additional impact rows were created relating to these costs and residual GHG emissions. These were estimated by extrapolating the UK impacts in proportion to the GHG emissions from each sector outside the UK. These estimates carry far lower confidence than those for the UK as they assume the same mix of processes to be replaced but are used to indicate the extent to which these additional effects might be relevant.

Price increases will affect households and owners of capital as the previous nominal expenditure pattern (i.e. household consumption and capital formation, respectively) will not be able to buy as many products and services. It is possible that households will try to increase their income (i.e. employee compensation) such that their real spending can remain constant, and that owners of capital will try to increase their return (i.e. gross operating surplus) such that their real capital formation can remain constant. In each case, prices would increase more than that required to simply pass on the initial cost of decarbonising the industrial processes. To assess these potential further price increases, we performed additional input-output analysis as described above but endogenising either "labour" (employee compensation and household spending), or "capital" (gross operating surplus and capital formation). Practically, this meant incorporating the vectors representing these flows into the inter-industry spending matrix (usually denoted Z) that was used to create L. This was done for the component of these flows relating to the UK (e.g. employee compensation for the UK rather than globally). The results obtained when endogenising labour are relevant to impacts on competitiveness as they correspond to a situation in which the price increases include increasing nominal domestic in line with prices. The results obtained when endogenising capital are relevant to impacts on household expenditure as the correspond to a situation in which the price increases include increasing nominal capital formation in line with prices.

The overall approach used for "pass it on" means the 2019 inter-industry structure is assumed to be representative when assessing the way in which costs are passed along supply chains. Implicitly, therefore, there is no consideration of substitution or elasticity effects. These would be necessary if fully assessing an effect on prices but not for providing an upper bound on prices (within the scope of the original N-ZIP model results and other caveats above) as these effects would act to reduce prices (e.g. if a commodity becomes more expensive, that would create an incentive to reduce or replace it with an alternative if that alternative is cheaper). Using the 2019 inter-industry structure also excludes costs or profits that might occur in industries that do not yet exist. The price increases are presented relative to 2019 spending patterns. If Gross Domestic Product (GDP, aggregate spending) increases relative to the use of the physical processes that drive these costs, then the price increases due to the industrial emissions reduction would be proportionally lower.

2.5. Illustrative scenario 3: "spread it out"

In the "Spread it out" illustrative scenario, the additional costs relating to each product's supply chain are distributed along the supply chain in proportion to where value is added. This illustrative scenario represents a world in which the businesses do not want to (or cannot) pass on costs to final consumers but do want to minimise the share of the cost that they face. In fact, there is evidence that pass-through of carbon costs is currently limited under the EU ETS (Stede et al., 2021). In this situation, it seems feasible that each company might absorb costs in proportion to their motivation to maintain the activity of that supply chain, and that their level of motivation (at this level of aggregation) might be proportional to the value that they add (i.e. the GVA that they make).

These results were also calculated using IOA but the method is more involved than for the "Pass it on" scenario. The mathematical formulation for this approach is expanded upon in Appendix A but is summarised below. To our knowledge, the specific method is novel but comparable approaches have been developed elsewhere to explore other considerations such as shared emissions responsibility (e.g. Jakob et al., 2021; Lenzen et al., 2007; Xu et al., 2021). L. Wang et al. (2020) and Z. Wang et al. (2017) have made use of similar techniques in splitting GVA along global value chains, but here we give it meaningful application in considering where the relative motivation to maintain these value chains might be.

Firstly, embodied costs were calculated in the same way as the "Pass it on" scenario.

The embodied GVA was then calculated in a similar way (i.e. using IOA but with GVA as the extension vector rather than the results from N-ZIP). The GVA embodied in each product should ordinarily be the same as the final consumption for those product groups, but calculating it in this way enabled the fraction of the total contribution from each sector to be calculated (e.g. the amount of GVA in the iron & steel sector due to final consumption of vehicles).

Next, the embodied costs for each final product were shared between the industries in its global supply chain, in proportion to the contribution to embodied GVA occurring in each supplying industry. For example, the embodied GVA in the whole supply chain for UK vehicle manufacturing sector is taken to be £37,580 M, of which the GVA in the UK fabricated metals sector ultimately driven by the production of vehicles is £750 M. The modelled net cost of low-carbon technologies in the UK vehicle manufacturing sector in 2030 is £38 M. Therefore, £760 k (£38 M x £750 M/£37,580 M) would be "allocated" to the UK fabricated metals sector, corresponding to the costs associated with decarbonising the UK vehicles manufacturing supply chain.

Finally, the costs allocated to each industry in the previous step (i.e. relating to each of the final products that it is in the supply chain for), were summed. That is, the £760 k from the example above would be added to the portion of the costs of decarbonising the production of machinery that is allocated to the UK fabricated metals sector, and so on for all products that drive activity in the UK fabricated metals sector.

2.6. Sensitivity analysis

Our analysis is dependent upon the costs and emissions projections that the N-ZIP model creates. In turn, the results from N-ZIP are dependent upon the parameters and assumptions within that model (Gailani et al., 2021). To explore the sensitivity of our results to these changes, N-ZIP was run with three additional alternative sets of parameters and the resultant projections were used as inputs into the analysis reported here.

The three additional sets of parameters were.

- High capex: the capital expenditure (capex) for the low-carbon technology options was doubled.
- High fuel costs: the fuel costs were increased in line with recent increases (Gailani et al., 2022). This increases the cost of conventional fuel options but also of blue hydrogen.
- High CO_2 transport and storage costs. CO_2 transport and storage costs were given a floor of £40/t (in the default "balanced" pathway, it settles to around £5 to £15/t by the mid-2030s) to reflect the possibility that these supporting activities are far more difficult than anticipated.

3. Results & analysis

3.1. Illustrative scenario 1: take the hit

The bold, dark purple columns on the right-hand plots of Fig. 4 illustrate the net cost increases due to adopting the low-carbon processes. More generally, Fig. 4 compares the cost of the conventional ("baseline") emitting processes to the alternative low-carbon processes, normalised to the gross operating surplus made by each group of industrial sectors (in 2019). The left-hand plots illustrate total process costs, while the right-hand plots highlight the difference between the baseline and low-carbon processes. In each sector group, the low-carbon process costs (i.e. annualised capex, opex, energy costs, and infrastructure costs, solid green columns) are greater than the baseline process costs (hatched red columns) if the carbon price (grey columns) are not included (the low-carbon options cost less if the carbon costs are included; within the N-ZIP model this is what causes their adoption). These gross cost increases are shown by the hatched orange columns. In most cases, fuel savings are available through resource efficiency and energy efficiency (REEE, light blue columns). These savings reduce the gross cost increases due to adopting the low-carbon processes to the net cost increases (dark purple columns). The REEE savings are illustrated separately as it is possible that in some cases these opportunities could be taken without the adoption of the further low-carbon technologies. The gross cost increases might reflect how companies therefore view the low-carbon options, while the net costs reflect the net cost if the efficiency savings are included.

The costs of emitting processes (i.e. capex, fixed opex and variable opex) are less than the gross operating surpluses generated by sectors – both with the low-carbon options and the baseline technology options (i.e. they come to less than 100% in the plot). However, while the expenditure on emitting processes is sometimes comparable in magnitude to surplus, it is the difference between the costs of the baseline and the low-carbon options that is most relevant. It is worth noting that this difference between the low-carbon and baseline process costs is typically modest relative to the costs themselves (i.e. in most cases the baseline and low-carbon process costs are similar).

Fig. 4 includes the carbon costs of residual GHG emissions (at the relevant carbon price for the corresponding year). On the right-hand plots, these are the full carbon costs (rather than the difference in costs); this is because although these costs are far less than they would be without the low-carbon processes (i.e. there is a saving relative to the baseline carbon costs), they still potentially present a cost to the sector that is in addition to the status-quo. In earlier years, the carbon cost relating to residual emissions can be greater than the costs of the low-carbon processes that are adopted.

It is possible that additional costs will cause downward pressure to be exerted on employee compensation. Fig. 5 illustrates the cost increases relative to gross operating surplus, employee compensation, and GVA. The dark purple columns (relative to operating surplus) are therefore identical to those in Fig. 4. The mid- and light-purple columns indicate the extent to which absorbing these costs would directly impact wages if the costs were either entirely met by a reduction in wages, or met by a reduction spread across GVA (the sum of employment, operating surplus and taxes net of subsidies). For most sectors, employee compensation is greater than, or similar to, operating surplus. However, for the mining and extraction sector it is much lower and (apart from any other

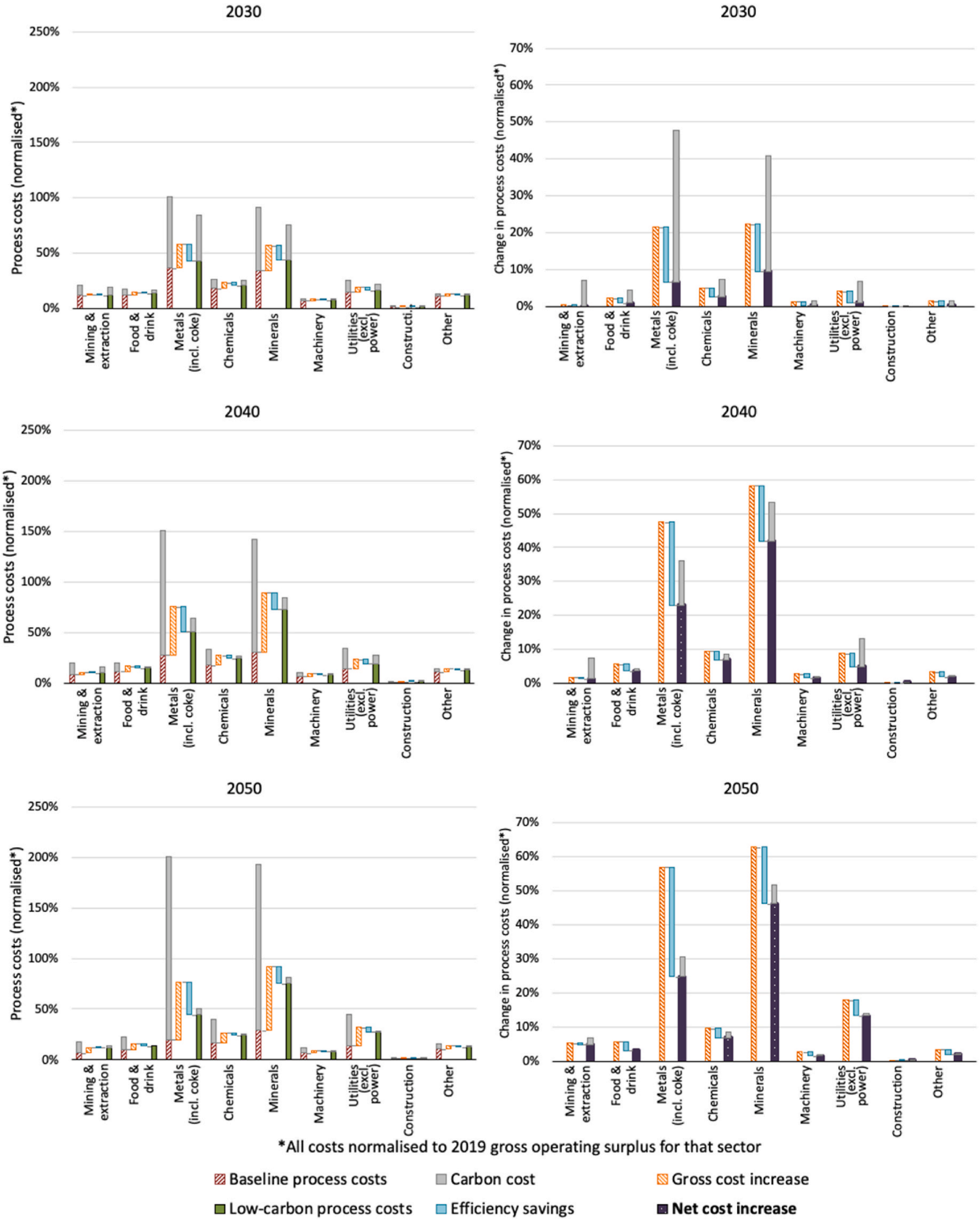

Fig. 4. Cost of decarbonising processes as share of profit generated by industrial sectors.

considerations) much less capable of absorbing any costs.

For several sectors, the cost increases are modest (less than 5% of current gross surplus) until the 2040s. However, estimated cost increases for the metal production sectors and non-metallic minerals sectors (cement, lime, ceramics) are much greater. These approach 26% and 55% respectively by 2050. By 2050, the extraction sector (mainly mining) and utilities sector (the costs are mainly due to waste treatment) also face cost increases of around 20% of their current gross surplus. For comparison, Fig. 6 shows the variation in sectoral gross operating surpluses since 1997 (normalised to total output), derived from HM Government (2022) statistics. While this has remained relatively consistent for some sectors (e.g. food and drink), the metals and non-metallic minerals sectors have experienced significant fluctuation. Over the last decade, they have each achieved relative increases in their gross operating surplus that exceed the decarbonisation costs explored here. Nonetheless, these sectors may need assistance in meeting these costs and merit attention.

3.2 Illustrative Scenario 2: Pass it on.

If the costs of decarbonisation can be passed on to customers, then they will be less discernible. This is partly because the net

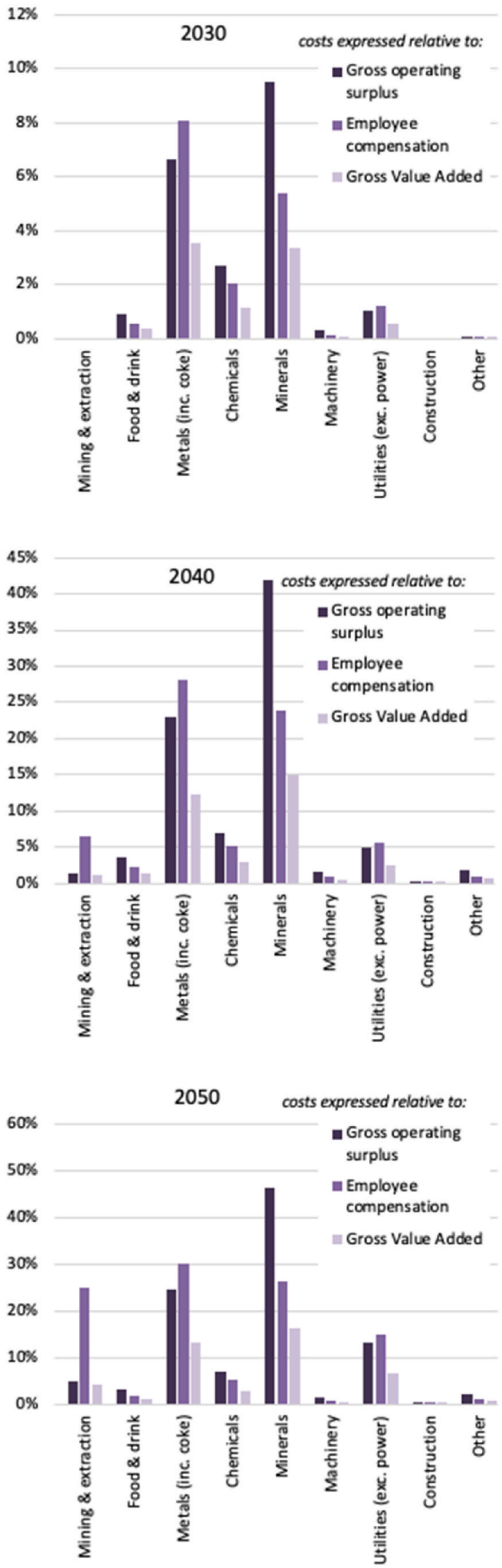

Fig. 5. DIrect costs to decarbonise industrial processes, expressed relative to gross operating surplus, employee compensation, and GVA.

decarbonisation costs represent a relatively small proportion of the total cost of the products (in contrast to representing a larger proportion of the gross surplus gained by producing them). It is also partially because the industries that face the greatest direct costs tend to produce intermediate products that are incorporated into higher-value products, somewhat diluting these costs if they're considered in terms of final products. Fig. 7 (left) illustrates the relative price increases that could occur if the costs of decarbonising industry are fully passed on to customers. For example, the price of utilities (excluding power) could increase by 4% by 2050 due to industrial costs being passed on. The largest increases potentially relate to costs from the decarbonisation of industry in the rest of the world (RoW, the hatched red bars). The exception is the utilities sector where the products (waste treatment is the main source of costs here) are necessarily localised. The RoW component relates to both overseas activity that supply products for intermediate use (i.e. business to business) in the production of UK products, and to overseas activity directly supplying UK final consumption (i.e. business to consumers). There is greater uncertainty over these RoW costs as the input cost projections (from N-ZIP) relate specifically to UK industry and are extrapolated to the RoW industries. However, at the very least it can be noted that the average level of emitting activity (and therefore GHG emissions) per unit of value supplied is greater for these RoW sectors than for the UK sectors.

Subject to the projected carbon prices, passing on the cost of residual GHG emissions (i.e. those remaining even after low-carbon technologies are adopted, the grey bars in figures) is potentially a large component of price increases; comparable to the net cost of the processes themselves until around 2040. However, there is greater uncertainty about how these might be applied – especially as they potentially represent financial flows that could be redistributed. This also suggests some scope for flexibility in how policy implements a carbon price.

The right-hand side of Fig. 7 shows these same costs but aggregated by expenditure patterns rather than by product groups. Because products are bought in different proportions in different income groups, the price increases represent different weighted averages of the product price increases. Results are presented for the mix of products bought on average by different income groups, from the lowest to highest deciles of household income. There is relatively little difference in the total cost increases between income decile groups; the average increase in prices is similar regardless of income group. If considering components of the cost increases, that due to UK industrial decarbonisation is slightly more for lower income groups (it varies from 0.11% up to 0.14% in 2040 and from 0.17% to 0.24% in 2050) but this is almost balanced by the cost increases due to RoW industrial decarbonisation being slightly less for lower income groups (varying from 0.27% to 0.30% in 2040 and from 0.38% to 0.44% in 2050). The price increases due to residual emissions being priced in and then passed on would amount to around 0.47% in 2040 and 0.24% in 2050, but as noted above these are different in nature to the cost of the low-carbon production technologies and provide scope for redistribution.

Fig. 8 illustrates the modelled price increase for individual product types under the "pass it on" assumption. These results are more relevant to questions around the potential effect of price increases on competitiveness (as they relate to product types), whereas Fig. 7 is more relevant to questions around the effect on consumers (as they relate to mixes of products). The results are less aggregated than the results presented in Fig. 7, and show greater range. These results relate to goods produced by UK industry; they include some costs relating to RoW industry in order to supply intermediate products to UK industry (business-to-business sales) but (in contrast to Fig. 7), they do not include costs relating to RoW industry creating products for direct sale to UK consumers (business-to-consumers). The RoW components of the price increases are therefore somewhat lower on average in Fig. 8 than in Fig. 7.

In a sense, a "worst-case" situation to mitigate against in terms of competitiveness would be to consider an eventuality in which UK industry and the majority of its supply chain is subject to a carbon price

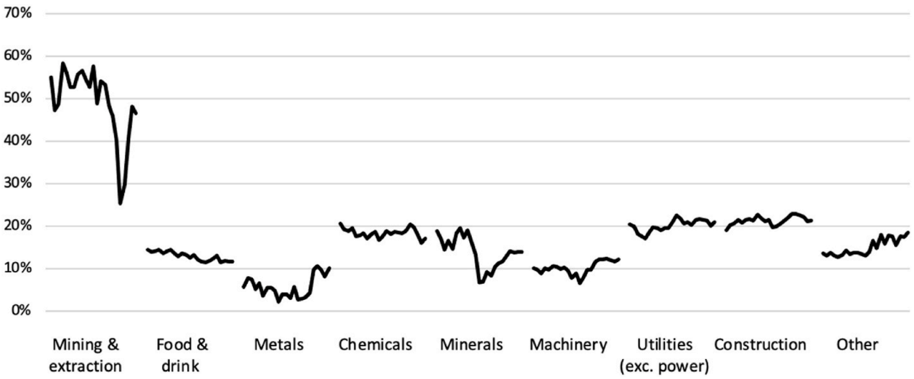

Fig. 6. Time series of sectoral profit margins (ratio of gross surplus to total output), 1997–2019.

and therefore adopts low-carbon technologies, whereas some overseas competition does not. In that extreme situation, if UK companies pass on all of their costs, the price increases illustrated in Fig. 8 would be experienced as price-premiums relative to competitors (more precisely, as changes in these price premiums relative to the status-quo). However, even in this extreme case, it is unlikely that all of these price increases would actually occur. For example, it is unlikely that a set of trade conditions would be adopted in which UK industry is exposed to price increases for intermediate products from overseas (red hatched bars) and carbon pricing (grey bars), while also competing with final products that do not have price increases from either of these components. The price components due to UK industry adopting low-carbon processes (dark blue bars) present a more congruent situation. These are the potential price increases that could indicate where a lack of competitiveness and carbon-leakage might be expected without further intervention. The orange bars relate to the additional price increases that would be needed in order to increase employee compensation in UK companies such that average household consumption could remain constant in real terms (i.e. increase in nominal terms, in proportion to these prices).

For most industrial sectors, these increases due to adopting low-carbon processes are less than 1% even by 2050 but there are several important exceptions. Notably, waste (13%), iron & steel (12%, 16% in 2040), glass & ceramics (8%), cement and lime (12%), dyes & agrochemicals (9%) and industrial gases/fertilisers (14%). These sectors deal primarily with bulk products and so could be well suited to carbon border adjustments.

3.2. *Illustrative scenario 3: spread it out*

Fig. 9 shows the additional cost of the low-carbon processes (i.e. as they are in Fig. 5 relating to the “Take the hit” scenario, but with the addition of a “non-industrial” sector to cover costs that are shared to these). However, here the costs are spread between sectors in proportion to the value that they add to each value chain. These results relate to the additional costs that UK sectors might face (i.e. their share of value chain costs) but these costs include those from UK industry (blue solid columns) and RoW industry (hatched red columns). In both cases only costs within the scope of N-ZIP (or the extrapolated equivalent for RoW industry) are considered. As in Fig. 5, the costs are presented as a proportion of each sector’s gross operating surplus, total employee compensation, and gross value added. They therefore provide an indicative illustration of the effect of these costs being taken from operating surplus, employee compensation, or GVA (their sum, plus taxes less subsidies).

The costs are less varied between sectors, compared to those relating to the “Take the hit” scenario; they do not exhibit the higher costs observed in Figs. 4 and 5. By 2050, the greatest cost is incurred by the machinery and “other industry” sectors (around 7% of gross operating surplus). It is interesting to note that the costs that these sectors would face increase while those that the metals production sector faces reduce (relative to the “take the hit”/direct costs illustration); they capture a greater proportion of the GVA of that value-chain and might be more incentivised to absorb costs. In contrast to Stede et al.’s (2021) results, no sectors experience increases greater than 5% of GVA if costs were spread in this way. The results are not directly comparable as the present study includes cost of abatement combined with a greater carbon price but it is also notable that the sharing of cost burden along value chains could mitigate the cost increases below the indicator used by the EU to assess carbon leakage risk (Sato et al., 2015).

In many cases, a large share of costs is passed on from RoW industry rather than originating with UK industrial decarbonisation. This reflects UK industry’s extensive involvement in international value chains in which it adds considerable value, but also suggests that future pressure on prices may come from overseas. That is, for some products, international suppliers of intermediate products increasing their prices (as they decarbonise or face carbon pricing) might have more effect on margins than the adoption of low-carbon technologies in the UK.

3.3. *Sensitivity analysis*

If we change the input assumptions to the N-ZIP model, the costs that it calculates inevitably change. These changes affect the cost effects calculated in this study. These are illustrated in detail in Appendix B. However, for the three variations modelled here, the effects are less than might be anticipated. In the cases that capex items are doubled, or that CO_2 transport and storage costs are increased (to a floor of £40/tonne), there are no major changes in the pattern of cost increases, and the incremental increases relative to the central set of results are small (typically less than 0.1 percentage points).

A significant increase in fuel costs (in line with the assumptions of Gailani et al. (2022)) has a more noticeable effect but, even with extreme assumptions, the general nature of the cost increases and conclusions is unlikely to change. In this case, N-ZIP models a delay in decarbonisation which causes greater carbon costs around 2040 but a slightly lower increase in the process costs. Overall, it results in a larger increase in prices if costs are passed on. If the costs are spread out, then there may be some further reduction in variation between sectors (relative to the central set of results), with the minerals sectors experiencing lower costs.

4. Conclusions and policy implications

The potential price impacts of pursuing a deep decarbonisation pathway for UK industry have been explored under three illustrative scenarios. These scenarios consider the costs of decarbonising industrial processes in the UK. The results indicate, that in the longer term, most sectors are unlikely to completely absorb the cost of switching to low-

Fig. 7. Price increases – by product group (left) and by expenditure patterns (right).

carbon technologies. This particularly applies in the period after 2035 when more extensive decarbonisation is required under the pathways examined. It is also most difficult for the more emissions-intensive sectors, such as metal production and non-metallic minerals, to absorb abatement costs.

Considerable cost savings may be possible through resource-efficiency and energy-efficiency measures. Without these, the net costs of emissions abatement would be greater. In many cases, adopting efficiency measures will complement a switch to low-carbon production; it is important that these synergies are realised. Otherwise, a later adoption of more extensive decarbonisation measures (once some of the lower hanging fruit have been taken) may be more economically

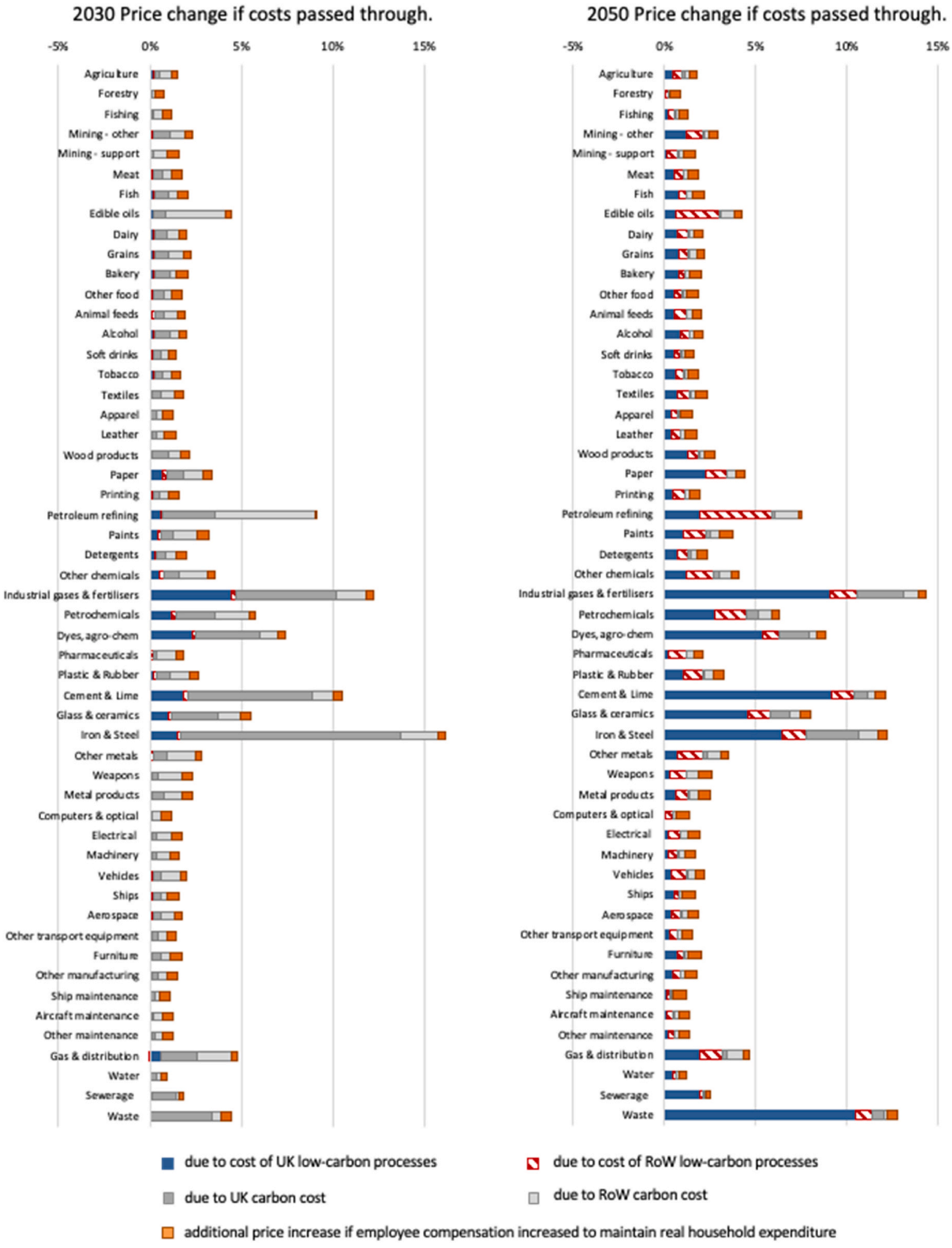

Fig. 8. Price increases of product types when costs are fully passed through.

challenging.

If the costs of decarbonisation can be passed on to customers, then the increase in the price of most goods will be modest. The relative aggregate price impact would also be similar among all income groups. That is, if the costs are passed on then they are likely to result in price increases that are similar (in relative terms, on average) for households with different incomes. Typical cost increases in final goods would be less than 0.5% by 2040, and less than 1% by 2050 (excluding carbon and indirect costs).

UK industry has a relatively low carbon intensity relative to its output (in financial terms). Overall, if decarbonisation ambitions (or effective carbon prices) are consistent with that internationally, it is quite possible that at least some parts of UK industry could gain a competitive advantage overall rather than a disadvantage. However, if

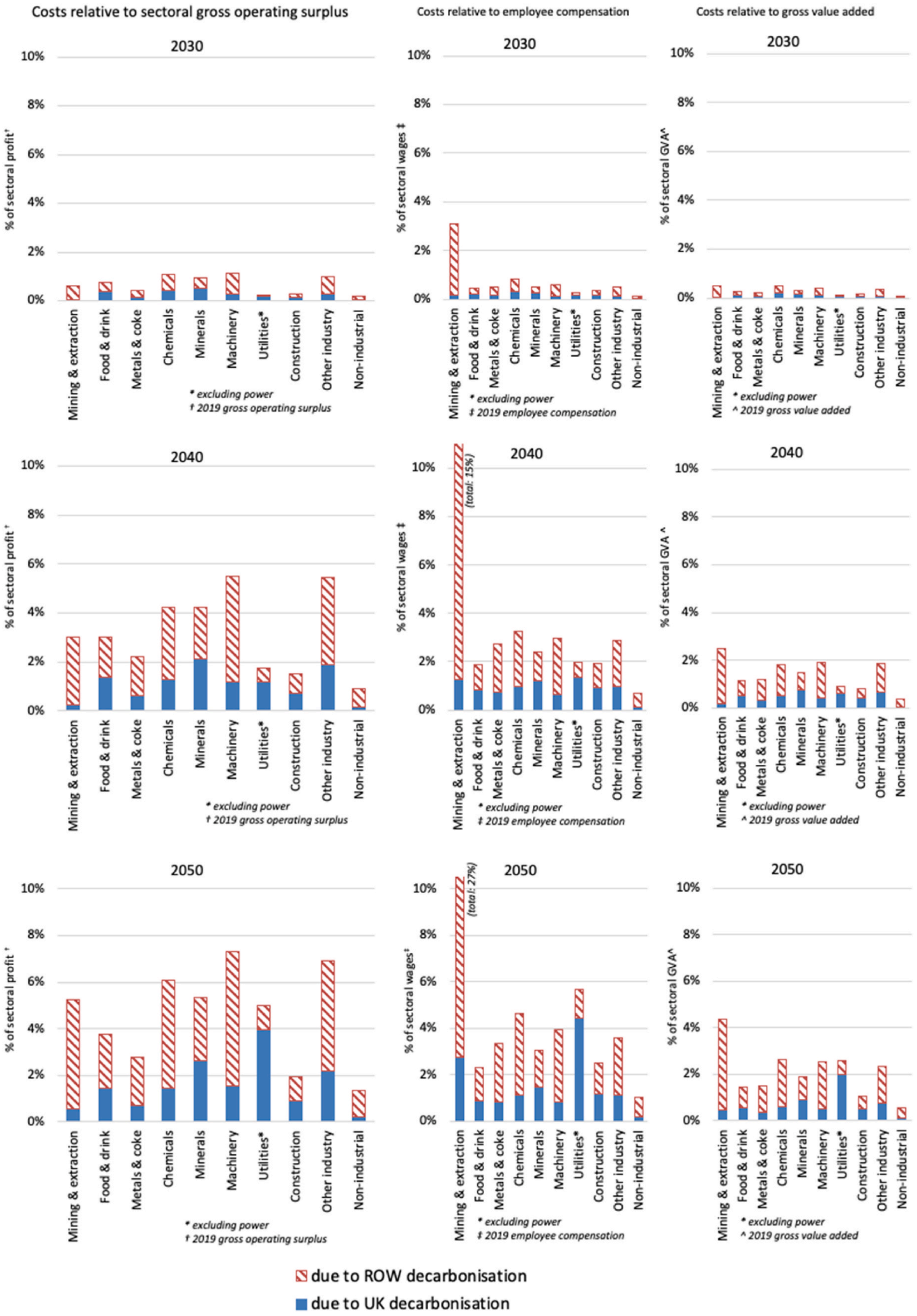

Fig. 9. Additional costs if spread along supply-chains.

UK industry ends up competing with products that do not include the cost of decarbonising their supply chains then some sectors will face difficulties. Those sectors most likely to be affected include: non-metallic minerals (cement, lime, glass, ceramics), iron and steel and some chemicals (industrial gases, fertilisers, dyes, agro-chemicals). These sectors typically produce bulk materials and may require the protection of a mechanism such as carbon border adjustments.

Future work could broaden this analysis to provide more specific results relating to other regions, and to include other decarbonisation costs that may occur in supply chains (i.e. beyond industrial processes). Additional analytical techniques (such as computational general equilibrium modelling) could also usefully explore other aspects of the way in which a transition to a low-carbon society might affect patterns of consumption and activity. In particular, the inevitable interactions and knock-on effects of these changes (for example as consumers and industry change the goods and services they use, and as employment patterns and productivity respond). Similarly, other techniques (for example agent-based modelling, ABM) might be more suited to exploring the potential effectiveness of policies designed to address some of the challenges that this work highlights.

The overall costs to decarbonise UK industry are small relative to the total value created. Concerns around pressures relating to competitiveness, equity, and price should not detract from ambitious action. However, some sectors will require support to ensure that they continue to compete if exposed to international competition that does not decarbonise.

Data statement

Detailed results are available in an Excel spreadsheet, available at (Bath DOI tbc).

CRediT authorship contribution statement

Samuel J.G. Cooper: Conceptualization, Methodology, Formal analysis, Writing – original draft, Writing – review & editing. **Stephen R. Allen:** Conceptualization, Writing – review & editing, Supervision, Funding acquisition. **Ahmed Gailani:** Conceptualization, Writing – review & editing. **Jonathan B. Norman:** Conceptualization, Methodology, Writing – review & editing, Funding acquisition. **Anne Owen:** Methodology, Data curation. **John Barrett:** Conceptualization, Funding acquisition. **Peter Taylor:** Conceptualization, Writing – review & editing, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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We are grateful for the input and suggestions of three anonymous reviewers in improving this article; especially relating to methodological points and scope.

Appendix A. Formulation of method for "spread it out"

This appendix provides a more detailed description of the method used in calculating the "spread it out" results. Here, our terminology assumes an industry-by-industry IOT format (i.e. "products" refer to the product output from an industrial sector), but the formulation is general to other formats such as product-by-product or supply-use.

Step 1. The total impacts (e.g. cost or emissions) embodied in consumption of final products are calculated in the usual way.

On an element-wise basis:

$$m_j = y_j \sum_{i=1}^{n} (e_i / x_i) l_{ij}$$

where m_j and y_j are the total impact embodied in product j and the final consumption of it, respectively. e_i and x_i are the direct impact and total output of industrial sector i. l_{ij} is the total (i.e. direct and indirect) activity in sector i that is required to support consumption of one unit of product j.

In matrix format:

$$M = E/X.L.diag(Y)$$

where M is a 1 x n vector of the total impact associated with the consumption of each product. E/X is a 1 x n vector of the direct impact from each industry divided by the output from each industry. L is an n x n matrix of the total requirements for each products, i.e. the Leontief matrix calculated as $L = (I - A)^{-1}$ in which I is the identity matrix and A is the direct requirements matrix. $diag(Y)$ refers to an n x n matrix in which the final demand for each product (1 to n) is given in the leading diagonal.

Step 2. The embodied GVA (gross value added) in products is equivalent to final purchases of those products. That is, the input-output framework is balanced so the GVA is the source of net-value that is eventually consumed.

Element-wise:

$$y_j = y_j \sum_{k=1}^{n} (v_k / x_k) l_{kj}$$

Where v_k is the GVA due to industry.

We can consider the proportion of this total embodied (final consumption) value of product *j*, that originates (is added) in sector *k*:

$$y_{kj} / y_j = (v_k / x_k) l_{kj}$$

In matrix format:

$$W = diag(V / X).L$$

Where W is an n x n matrix of the relative sources of total GVA; i.e. element $W_{kj} = y_{kj}/y_j$. V is a 1 x n matrix of GVA added by each industry.

Step 3. The impact associated with the final consumption of product *j* is then allocated to industrial sectors based on the proportion of the GVA of product *j* that they created.

Element-wise:

$$h_{kj} = \frac{m_j y_{kj}}{y_j} = (v_k / x_k) l_{kj} y_j \sum_{i=1}^{n} (e_i / x_i) l_{ij}$$

Where h_{kj} is the impact allocated to industry sector k due to its activity to support the supply chain for product *j*.

Step 4. Finally, for each industrial sector, the impacts allocated to it from the supply chain of each product are summed together.

Element-wise:

$$h_k = \sum\nolimits_{j=1}^{m} \frac{m_j y_{kj}}{y_j} = (v_k / x_k) \sum\nolimits_{j=1}^{m} \left(y_j l_{kj}\right) \sum_{i=1}^{n} (e_i / x_i) l_{ij}$$

Matrix format:

$$H = M.W^T$$

Appendix B. results for sensitivity analysis

This appendix summarises additional results relating to three variations in the N-ZIP parameters that affected the decarbonisation cost to be met. This additional analysis was used for sensitivity analysis.

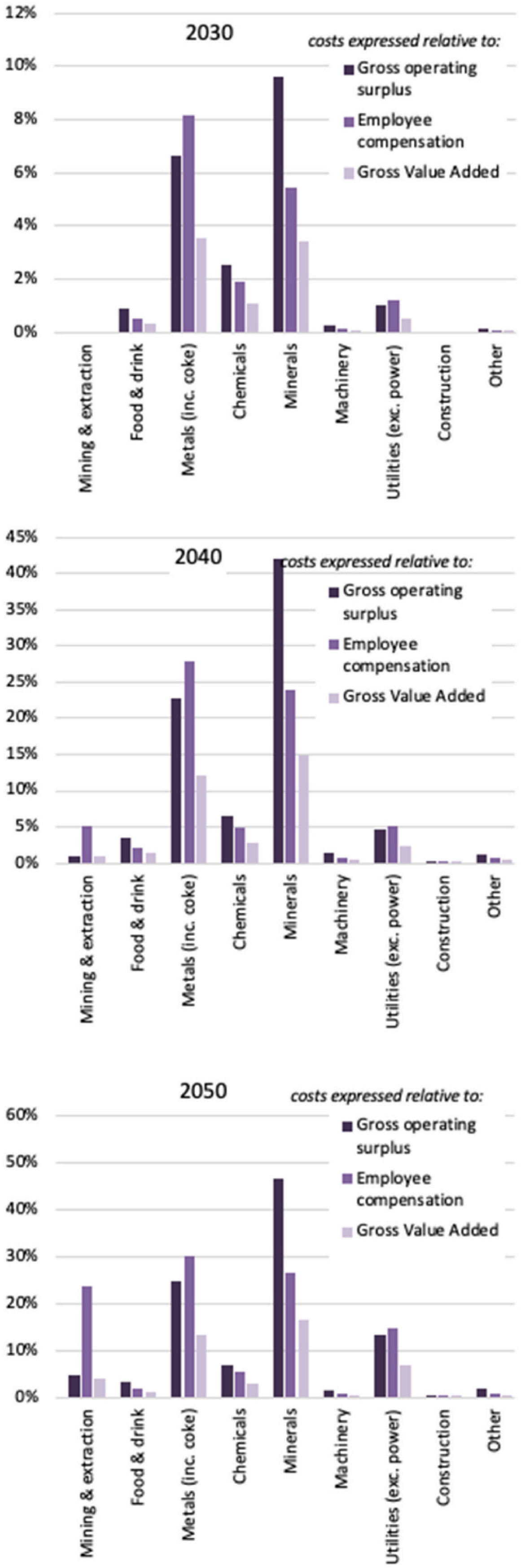

Fig. B1. Direct costs, high capex. .

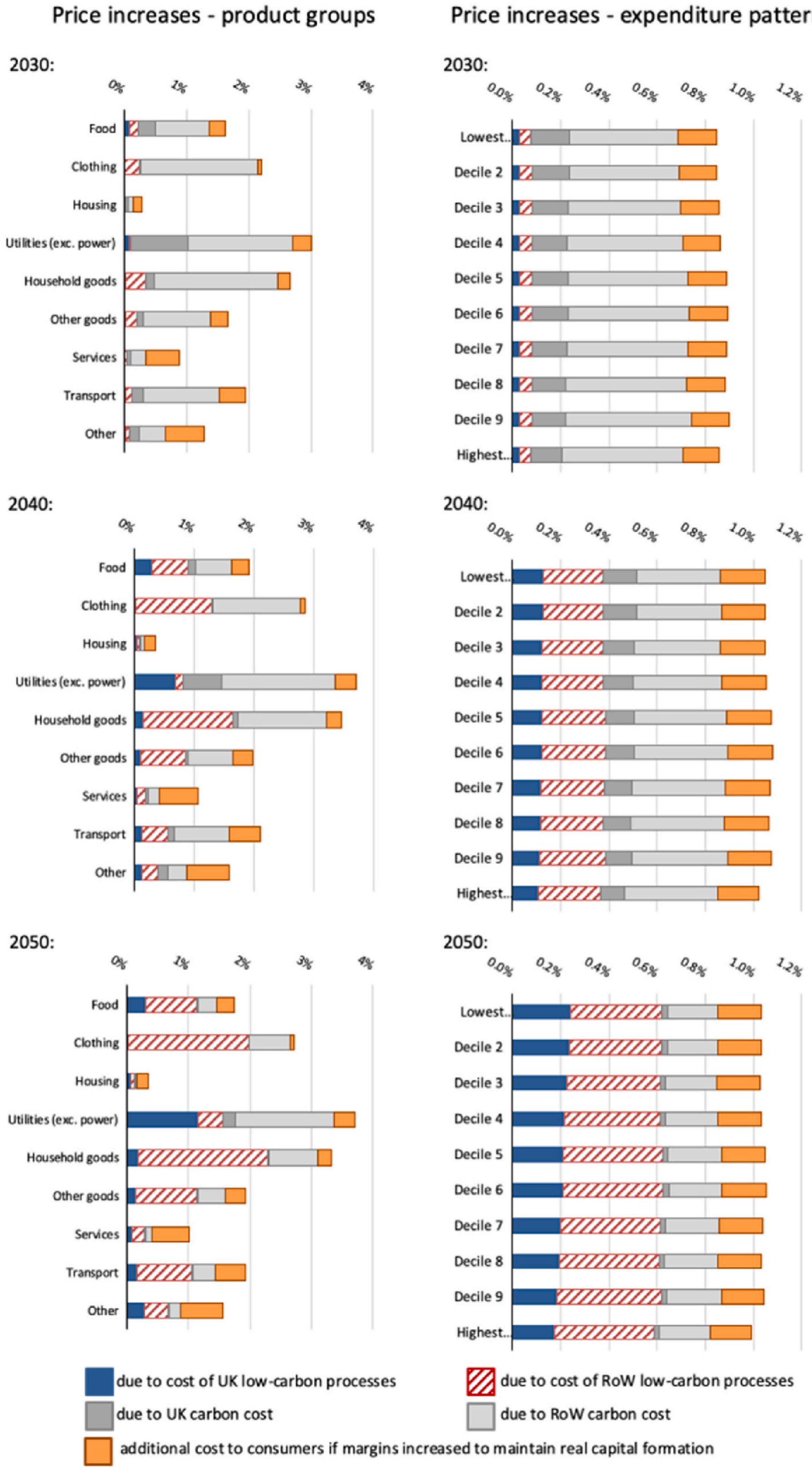

Fig. B2. Costs passed on to prices, high capex. .

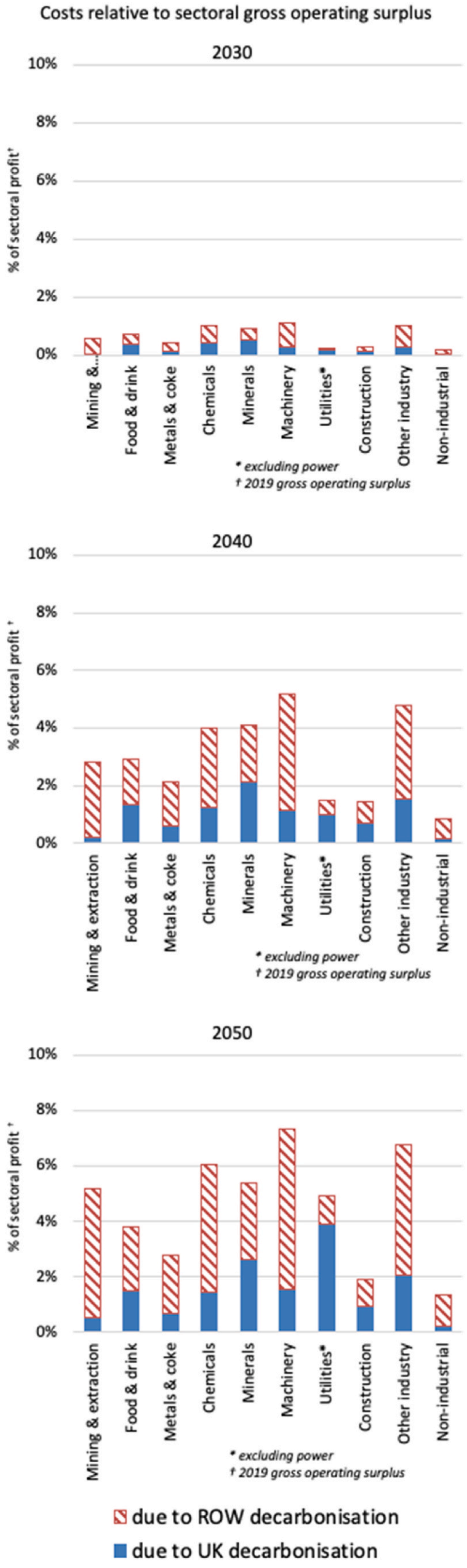

Fig. B3. Costs shared out, high capex. .

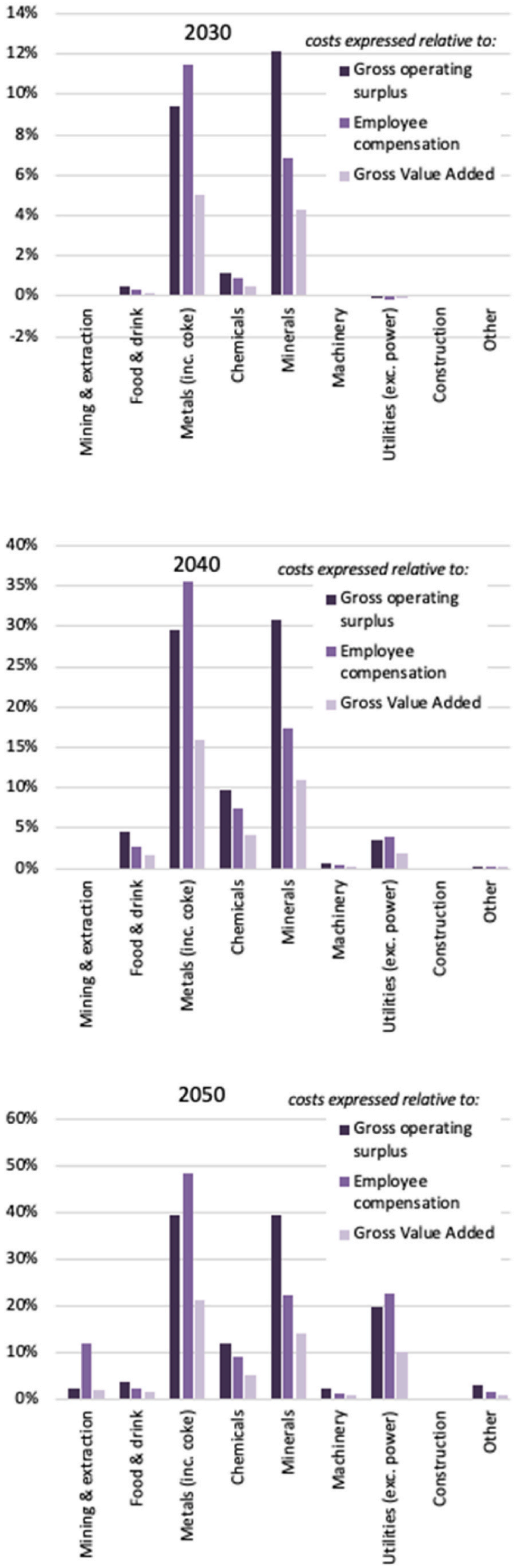

Fig. B4. Direct costs, high fuel costs. .

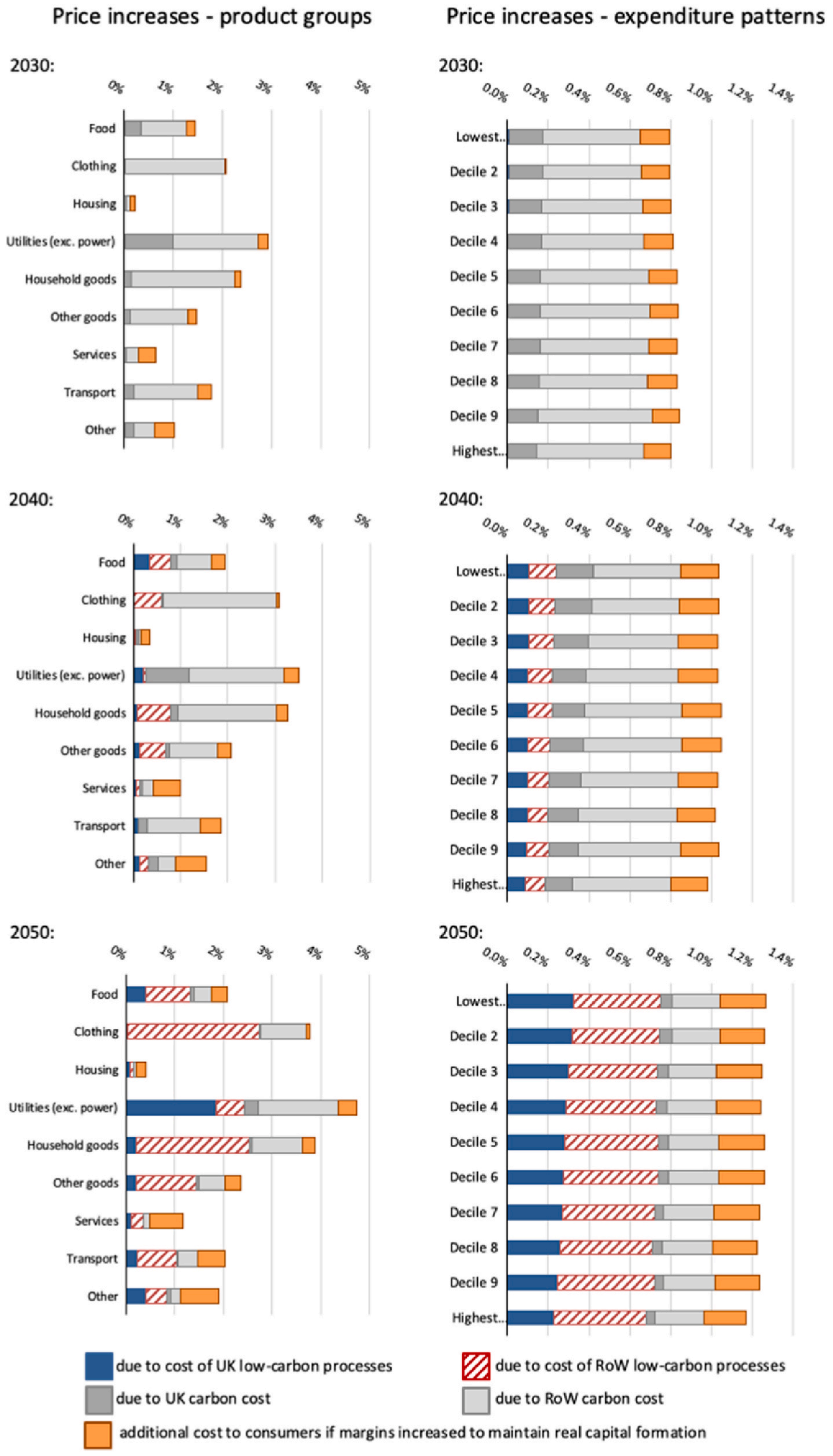

Fig. B5. Costs passed on to prices, high fuel costs. .

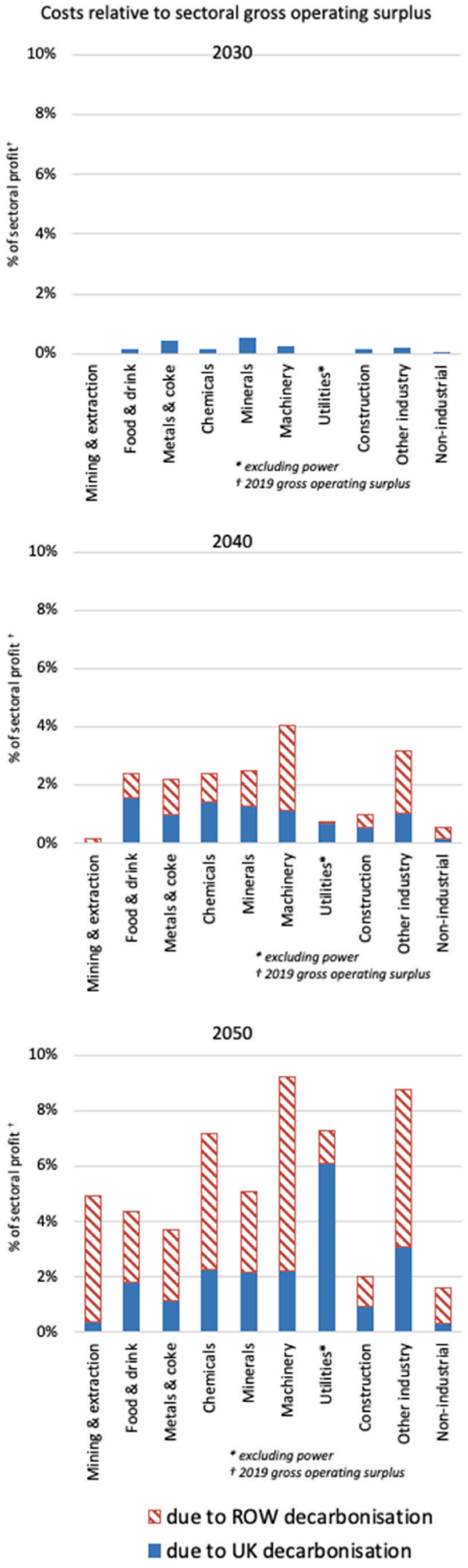

Fig. B6. Costs shared out, high fuel prices. .

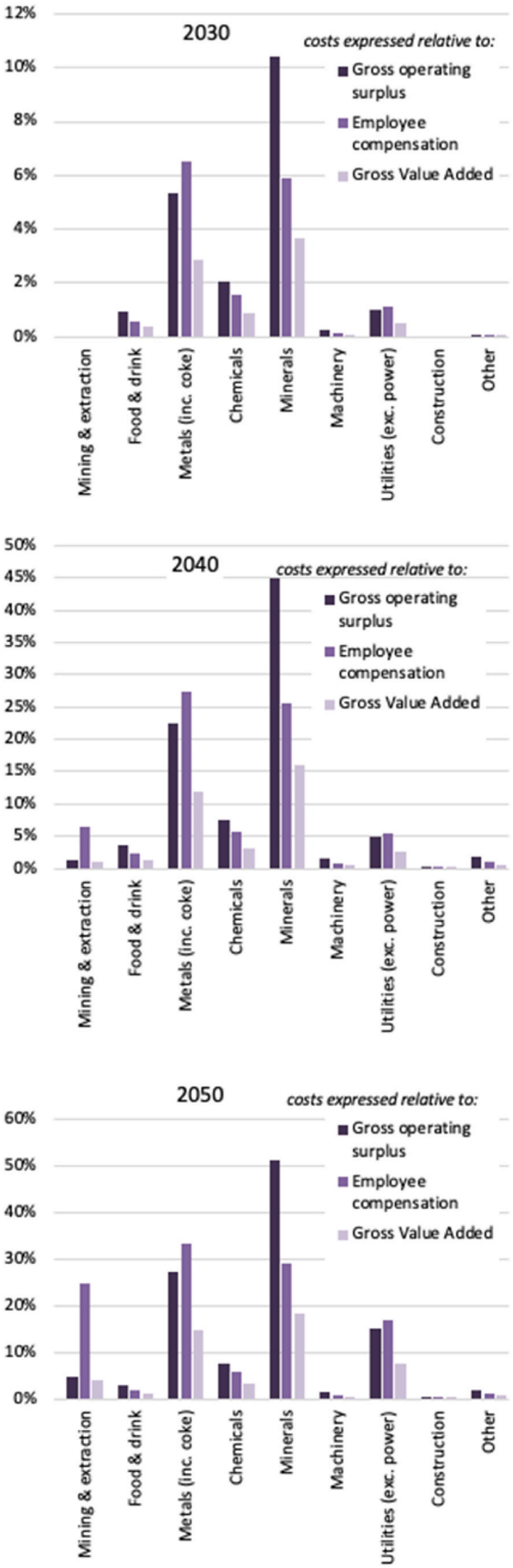

Fig. B7. Direct costs, high CO_2 T&S costs. .

Fig. B8. Costs passed on to prices, high CO_2 T&S costs. .

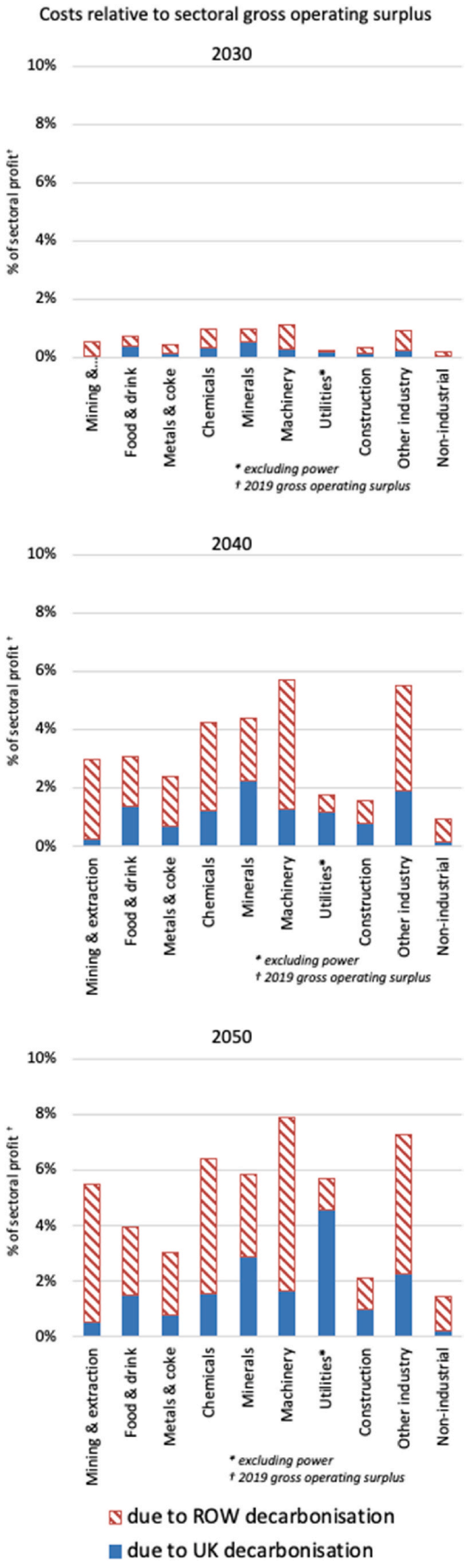

Fig. B9. Costs shared out, high CO_2 T&S costs. .

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