



Mapping regional vulnerability in Europe's energy transition: development and application of an indicator to assess declining employment in four carbon-intensive industries

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Abstract

Europe's transition to an energy system compatible with limiting global heating to 1.5 °C will require radical changes in energy systems. While this will create substantial new growth industries in clean technologies, some currently important economic activities will decline. The impacts of that transition will not be the same for all regions. We map the economic vulnerability of European regions to ambitious decarbonisation scenarios in terms of employment losses in four carbon-intensive industries. To do so, we develop a composite vulnerability indicator that combines each region's share of employment in those high-carbon industries with other dimensions of vulnerability and resilience. We then explore how regional patterns of vulnerability are influenced by the technology pathway to 2050, using four scenarios modelled using the European PRIMES model. We show that economic vulnerability to the low-carbon transition is regionally concentrated, with some regions combining high employment shares in industries expected to decline with weak adaptive capacity and high pre-existing unemployment. We also show that there is little variation in regional vulnerability arising from different transition pathways. All scenarios compatible with 1.5 °C involve large declines in all high-carbon sectors we analyse, and as a result, scenario variation does not lead to large variation in relative vulnerability of regions. The results highlight regions that may be in need of additional policy support to diversify their economies and achieve a just transition.

Keywords Regional vulnerability · Carbon-intensive industries · Employment

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1 Introduction

European regions have diverse industrial and socio-economic structures that have evolved over decades. The deep decarbonisation that is necessary to fight climate change will be felt differently in different localities. While some regions can be expected to benefit from the growth of low-carbon industrial activities, other regions, especially those traditionally dependent on high-carbon activities, may risk economic decline, job destruction, and social hardship.

Developing a better understanding about which European regions may be most vulnerable to the short- and long-term implications of low-carbon transitions is important to support policy efforts to limit potential negative impacts and to achieve a ‘just transition’ (McCauley and Heffron 2018; Newell and Mulvaney 2013). In addition, regional variation in vulnerability to decarbonisation could influence the politics of the transition, as companies and people at risk of losing their jobs in regions with declining high-carbon industries are more likely to oppose climate policies (Dijkstra et al. 2020; Tvinnereim and Ivarsflaten 2016).

This paper aims to map the economic vulnerability of European regions to ambitious decarbonisation pathways, using the ‘NUTS2’ level of regional classification used in Europe. We do so by developing a composite vulnerability indicator that combines the share of employment in a set of high-carbon industries with other dimensions of vulnerability. The paper first sets out the relevant literature and the conceptual background to assessing the regional vulnerability to low-carbon transitions. We then describe the data sources, and process of constructing the indicator, and show our results that map vulnerability across Europe based on a set of decarbonisation pathways developed with the well-established PRIMES model (Rodrigues et al. 2022).

2 Background

There is increasing recognition of the distributional impacts of climate policies which are felt differently across economic sectors, social groups and geographical space. Much of this literature has been framed as the need to have a ‘just transition’: shifting to a sustainable energy system in a way that is socially equitable and acceptable (McCauley and Heffron 2018; Newell and Mulvaney 2013). Policymakers have increasingly responded to such concerns. The European Union’s ‘Just Transition Mechanism’ (European Commission 2021) is an example of an attempt to target economic support to regions that are most affected by the energy transition.

The growing attention to the equity dimensions of the energy transition is reflected in a sizeable literature exploring the distributional impacts of climate change and energy policies (Feindt et al. 2021; Ohlendorf et al. 2021), including analysis of impacts on poverty (Dorband et al. 2019; Streimikiene et al. 2020), the income and expenditure of vulnerable households (Fragkos et al. 2021) and labour markets (Marin and Vona 2019). Such analysis reveals that the transition to a zero carbon economy can have very different effects on different social groups.

Inequality has historically not been a focus of energy transition modelling analysis (Klinsky and Winkler 2018; Rao et al. 2017), and as a result, the literature exploring the equity impacts of long-term energy transitions is rather sparse. Most of the relevant literature exploring distributional impacts of long-term energy scenarios has applied computable

general equilibrium (CGE) models to explore impacts of specific policies at the level of income groups—but with the geographic scale at the level of the nation-state (for example, see Cunha Montenegro et al. 2019; Fragkos et al. 2021), or large regions within countries (Cullenward et al. 2016). Generally, the literature has been focused on near-term impacts of specific policies (Fell et al. 2020).

There have been a few studies that attempt to assess vulnerability on the regional level. Wang et al. (2018) explored the relative vulnerability of coal mining cities in China, but not specifically in the context of expected long-term reductions in coal production. They concentrate on local coal output and price volatility as an indicator of the exposure of a region to the risk of reductions in coal production. Carley et al. (2018) map the vulnerability of US regions to renewable energy policies, incorporating residential electricity prices and poverty concerns into considerations of vulnerability. They focus specifically on a particular policy area (renewables) rather than the decline of specific high-carbon activities. Snyder (2018) and Raimi et al. (2022) both construct a vulnerability indicator for US counties, looking at employment in high-carbon industries and other measures of the sensitivity of regions (such as pre-existing levels of poverty). Their analysis is similar to ours, but neither includes an assessment of possible decarbonisation scenarios, and thus the decline trajectories of specific fossil-related activities. Finally, Skoczkowski et al. (2020) map the relative vulnerability of counties within the Polish region of Silesia, though with limited explanation of the rationale behind indicator choices. These studies all find that vulnerability differs substantially across regions within countries.

There have been some studies that explore regional vulnerability to specific sectors. The JRC recently conducted a detailed study specific to coal-related jobs in European countries (Alves Dias et al. 2018). There have also been some studies in specific countries on the job impacts of a shift away from internal combustion vehicles (Transport and Environment 2017). However, no previous studies have combined these into a broad perspective on regional economic vulnerability to a shift away from fossil fuels across the EU in the context of transition to climate neutrality.

This paper aims to provide such an analysis for the European Union and UK, while developing a conceptual framework and indicator approach that can be used more widely. The core contribution of this paper—with relevance for further research and for policy analysis—is to develop an approach to quantify the relative vulnerability of regions to declining fossil fuel employment, across a range of transition pathways.

3 Conceptual framework

Measures of economic dependence on specific industries are not common in the economic geography literature, and tend to explore dependence on single resources (oil, fisheries, etc.), often in developing country contexts (e.g. Allison et al. 2009). Other measures of regional vulnerability focus on economic openness that increases exposure to exogenous shocks; dependence on strategic imports (e.g. oil and gas) that increases vulnerability to price volatility in those imports; and export concentration that increases the impacts of demand shocks for exported goods (Briguglio et al. 2009).

Most literature assessing regional vulnerability in the context of climate change focuses on the physical impacts and potential damages caused by a changing climate. Analysis of this kind has used the IPCC's conceptual framework for vulnerability, in which vulnerability is a function of three constituent parts: *exposure* to some source of

disruption, *sensitivity* to that disruption and the *adaptive capacity* to respond and recover (IPCC 2007). For example, O'Brien et al. (2004) examined the regional vulnerability across India to physical climate change impacts, while Allison et al. (2009) conducted similar work on economic dependence on fisheries and corresponding vulnerability to climate change impacts.

We adopt the IPCC (2007) approach to vulnerability, but following Carley et al. (2018), we apply it to vulnerability arising from the transition towards a net zero carbon economy, rather than the expected physical impacts of a changing climate. Vulnerability, in our analysis, is understood as a function of the *exposure* of a region to likely job losses in carbon-intensive industries; the *sensitivity* of the region to those job losses; and the region's *capacity to adapt* its economy to decarbonisation pathways.

3.1 Exposure: job losses in the energy transition

Exposure, in our analysis, is related to the expected declines in fossil fuel-related employment as the use of fossil fuels declines. The first component of exposure is thus related to the current levels of employment in high-carbon sectors that are expected to be phased out as a result of the energy transition. Relevant high-carbon industries include, for example:

- Coal mining and processing, and the manufacture of coke
- Oil extraction, and to a lesser extent natural gas extraction
- Generation of electricity in fossil fuel power plants
- Support activities for fossil fuel extraction, including specialised consulting services
- Petroleum refining
- Manufacture of internal combustion engines (ICEs) and other equipment specific to fossil fuels (such as oil and gas boilers)

Industry classifications in national accounts and statistics do not always make it straightforward to identify high-carbon activities. This is either because data are collected or reported only at relatively high levels of aggregation, or because the economic activities cut across a number of traditional industry classifications. For example, there is no NACE category for machinery manufactured for coal mining; instead, such activities are part of 'Manufacture of machinery for mining, quarrying and construction'. Similarly, there is no split between renewable and fossil fuel technologies in the data related to electricity supply (Eurostat 2021a).

In this study, four major sets of economic activity have been identified that can both be measured with some confidence using official data and statistics from Eurostat (or national) economic accounts, and that can be expected to decline substantially in deep decarbonisation scenarios. These are coal mining, oil and gas extraction, fossil fuel processing (refineries) and the manufacture of internal combustion engines. We include only direct jobs, i.e. those directly involved in those activities. This understates the employment impact of industrial decline in fossil fuel sectors because it neglects the indirect job losses, for example in sectors that supply equipment and services to the four fossil fuel industries.

The second component of exposure is related to the expected reductions in these activities as the EU transitions to a near-zero carbon economy, explored through different decarbonisation scenarios produced by the European PRIMES energy system model (Capros et al. 2014). Our analysis is based on a set of decarbonisation scenarios that provide detailed techno-economic descriptions of how the European energy system can develop

to reach the 2050 target of climate neutrality (Rodrigues et al. 2022). Such scenarios illustrate, for example, the degree to which coal production in the EU could decrease.

We measure regional exposure as an outcome of the technology pathway to deep decarbonisation, rather than in terms of specific policy instruments as in Carley et al. (2018). The aim of the analysis is to identify the underlying reliance of different EU regions on specific technologies and related high-carbon activities that are expected to be phased out or substantially reduced in a decarbonised Europe. In doing so, we acknowledge that the geographic incidence of climate policies is likely to influence relative regional economic vulnerability to deep decarbonisation, for example by disproportionately burdening rural rather than urban communities with higher mitigation costs. Other studies have explored dependence on economic activities that might be expected to bear heavy costs (i.e. energy- and carbon-intensive sectors, such as cement, steel and chemicals) in a decarbonisation scenario (Paroussos et al. 2015), or the geographic vulnerability of consumers to high energy and carbon prices (Carley et al. 2018). Such effects require assumptions to be made about the specific policy mix, including assumptions about policy choices with respect to revenue recycling of carbon taxation or the structure of labour and energy markets (Fragkos and Paroussos 2018), and are thus much more uncertain than the decline in specific high-carbon activities, which are not compatible with ambitious emission reduction targets.

In using PRIMES model projections to explore industry decline scenarios and regional vulnerability, we make three important simplifying assumptions. First, we assume that the reduction in national output of each high-carbon industry is distributed proportionately across all NUT2 regions of the country that are involved in that industry. This assumption is necessary because PRIMES provides data for each country, but not for sub-national regions within countries. Second, for vehicle production, we assume that export markets follow the same trajectory as the EU and UK, so that internal combustion vehicle exports decline in line with the decline in European and UK domestic market for such vehicles. We thus assume that vehicle deployment in the model directly corresponds with vehicle production. Third, we assume that employment in each sector scales linearly with the relevant output of each sector. In other words, a 50% decline in coal production is assumed to result in a loss of 50% of associated jobs. Although this assumption is clearly a simplification, model-based analysis with CGE models (Fragkos et al. 2018; Paroussos et al. 2020) that consistently capture product, capital and labour market changes has shown that the impacts of decarbonisation on the output and employment of specific sectors are at comparable levels.

We focus our analysis on the scenario outcomes in 2035. We choose this year because it is sufficiently far into the future to see major changes in the four industries of interest, but not so far as to render current employment patterns irrelevant as a basis for comparison. Because there is relatively little time to 2035 for substantial divergence in mitigation pathways, we also explore the results for 2040 (these are reported in supplementary material).

For each region (r) and industry (i), the number of jobs expected to be lost is defined as:

$$\text{Jobs lost}_{i,r} = 2016 \text{ employment}_{i,r} * (1 - 2035 \text{ output}/\text{base year output}) \quad (1)$$

where ‘output’ relates to the output of each industry for the region’s respective country. The measure of output is specific to each industry and is based on physical units (e.g. the amount of coal, oil and gas extracted; the amount of fuel produced in refineries; or the numbers of new internal combustion engines sold).

Our measure of exposure for each region across all industries (J) is therefore given by:

$$Exposure_r = \frac{\sum_i^I jobs\ lost_{i,r}}{total\ 2016\ employment_r} \quad (2)$$

Section 5.2 describes in detail how we collected data on 2016 employment in the high-carbon industries we consider.

3.2 Sensitivity: unemployment

Our measure of exposure focuses on the share of a region's direct jobs that are threatened by the decline of high-carbon industries. Regions with already high levels of unemployment are particularly sensitive to further job losses, with fewer opportunities for laid-off workers to be immediately hired in other sectors and businesses. The literature on regional resilience notes that regions with high existing levels of unemployment are more sensitive to transition shocks (Briguglio et al. 2009; p. 7). We therefore use a region's current level of unemployment as a measure of its sensitivity, drawing on Eurostat's regional database (Eurostat 2021a).

A richer measure of sensitivity would be desirable, such as the share of people 'at risk of poverty or social exclusion' (Eurostat 2021b). This measure would combine joblessness, low income and poor material living conditions. One could also consider inward and outward migration (labour mobility) trends to analyse sensitivity. However, such indicators are not available for all member states at the NUTS2 level. The literature on 'just transitions' also highlights other dimensions that might lead regions to have a greater sensitivity to job losses. These include income levels (with low-wage regions having higher sensitivity) and regions with high proportions of social groups that have been marginalised in some way (typically racialised minorities) (Carley and Konisky 2020).

3.3 Adaptive capacity: innovation potential

Regions differ in their capacity to recover from lay-offs associated with the decline of locally important industries. Literature suggests, for example, that regions with higher levels of education will be better able to adapt to exogenously driven structural change (Hane-Weijman et al. 2018). Empirical analysis by Bristow and Healy (2018) showed that regions identified as innovation 'leaders' were better able to resist the 2007–2008 economic crisis, and recovered faster from it, suggesting an important role for innovation in a region's capacity to adapt following shocks.

In this analysis, we use the European Regional Innovation Scoreboard (RIS) as our measure of adaptive capacity. The RIS provides a measure of each region's innovation capacity, including educational attainment and labour skills (JRC 2019). We acknowledge that there may be other important factors related to innovation, such as the quality of regional infrastructure, human capital and entrepreneurial potential as well as the positioning of regional industries in international value chains (JRC 2019). However, the regional innovation scoreboard provides a good proxy indicator of key dimensions of relevant adaptive capacity of EU regions.

We use the 2016 values, provided directly by the European Commission's Joint Research Centre. The RIS is itself a composite indicator. We remove the 'air pollution' sub-indicator since this provides a poor proxy for adaptive capacity. A disadvantage of the RIS is that it results in the exclusion of several small countries, and some EU regions

for which RIS data are not available. As a result, the analysis in this paper excludes Cyprus, Estonia, Malta, Luxembourg, Latvia and some Croatian regions. All other European member states, plus the UK, are included. Moreover, in some cases, RIS data are only available at the NUTS1 level. Where that is the case, we assume that all constituent NUTS2 regions have the same level of adaptive capacity as their ‘parent’ NUTS1 region.

Innovation is not the only dimension of adaptive capacity. Other aspects of adaptive capacity, such as social capital, have been explored at the regional level in previous studies on European growth and inequality (Muringani et al. 2021; Parente 2019). Future work could examine the extent to which social capital is an important component of adaptive capacity to respond to the declines associated with phase-out of high-carbon industries. However, data availability for social capital is typically weaker than for the elements of the RIS.

4 Constructing the vulnerability indicator: normalisation, aggregation, weighting

4.1 Normalisation

Normalisation is required to ensure that each component indicator is measured on a comparable scale, so that they can be aggregated into a composite vulnerability indicator (OECD 2008). Prior to normalisation, the exposure and sensitivity indicators were transformed to reduce skew.¹ In order to normalise the transformed data for the exposure and sensitivity indicators, we used the min–max method, using Eq. (3), where x represents the value of an indicator for a given region, while x_{\min} and x_{\max} are the minimum and maximum values for that indicator for any region.

$$x_{\text{normalised}} = \frac{x - x_{\min}}{x_{\max} - x_{\min}} \quad (3)$$

The regional innovation scoreboard also uses this approach. As a result, the indicators of exposure, sensitivity and adaptive capacity all represent the relative performance of EU NUTS-2 regions on a scale of 0 to 1.

4.2 Aggregation

The constituent parts of the vulnerability indicator (exposure, sensitivity and adaptive capacity) have to be combined in order to produce a single composite indicator. The most common aggregation procedure for composite indicators is additive, in which the (weighted) components are summed (OECD 2008). However, an additive approach would be inappropriate here, since it would imply full substitutability between the elements of the indicator, and this would not make sense for the context of our study here: no matter how bad a region’s adaptive capacity, having zero employment in high-carbon sectors should result in zero decarbonisation-related vulnerability. An alternative to an additive approach is to use a geometric weighted mean (OECD

¹ A natural log transformation was used for sensitivity, but this was unsuitable for exposure given the large number of zero values, and a square root transformation was used instead.

2008). The geometric approach ensures that a zero value for exposure results in zero vulnerability overall, while allowing some substitutability between elements.

The aggregation for the regional vulnerability indicator for a given region (r) is therefore:

$$Vulnerability_r = E_r^{w_E} * S_r^{w_S} * (1 - AC_r)^{w_{AC}} \quad (4)$$

where E_r , S_r and AC_r represent exposure, sensitivity and adaptive capacity for a given region r , while w_E , w_S and w_{AC} are the weights specific to exposure, sensitivity and adaptive capacity. For the equation above to hold, the weights must sum to 1.

4.3 Weighting

The purpose of weighting is to adjust the degree to which indicator components (exposure, sensitivity and adaptive capacity) can compensate for each other in determining the value of the composite vulnerability indicator (Greco et al. 2019). This is often loosely interpreted as the degree of importance that each component has, and in this sense, weights are value judgements (OECD 2008). The relative importance of the different components is a subjective choice informed by the purpose of the indicator. In this case, the indicator's primary purpose is to highlight the vulnerability of regions that have high direct employment dependency on activities that are expected to decline during the energy transition. We therefore give a higher weight to our measure of exposure ($w_E=0.6$), and a lower weight to the sensitivity and adaptive capacity measures ($w_{S, AC}=0.2$). This means that a region that has high exposure can reduce its vulnerability to decarbonisation through high adaptive capacity and low sensitivity, but that high exposure dominates the final indicator.

Other weighting choices are of course possible and would change the resulting measure of vulnerability to be more or less sensitive to variation in each constituent indicator. We test the implications of different weighting schemes to understand the sensitivity of the resulting ranking to the weighting choices. We explore both an 'equal weights' option, in which the three components of the indicator are weighted equally, and a weighting scheme that places even further emphasis on the exposure measure (with 0.8 for and 0.1 for both adaptive capacity and sensitivity). The results of this analysis are reported in the supplementary file.

There is a second possible purpose of weights in the construction of a composite indicator: to avoid double counting of indicators that are highly correlated, and that measure essentially the same underlying phenomenon (Greco et al. 2019). Where this is the aim, statistical methods such as factor analysis are used to ensure that the component indicators are weighted to minimise such double counting. In the current context, unemployment (our measure of sensitivity) does show a negative correlation with innovation, based on the 2016 data. However, the correlation is rather weak ($R^2=0.16$), and is therefore disregarded.

5 Data sources for exposure: employment in high-carbon sectors and PRIMES decarbonisation scenarios

Exposure relates to the job losses expected to arise from the decline of high-carbon activities. To calculate the exposure of EU regions to clean energy transition, we use data on existing employment structure in high-carbon industries in EU NUTS2 regions and

combine them with scenarios for European decarbonisation pathways, developed with the PRIMES energy model.

5.1 Scenarios of EU and UK decarbonisation pathways

The scenarios are consistent with the EU and UK goal for net zero emissions in 2050 and are reported in greater detail in (Rodrigues et al. 2022). The model-based scenarios explore stakeholder-designed narratives of the future energy system evolution and explore the role of specific mitigation options (e.g. electrification of end uses, renewable energy, hydrogen) towards achieving climate neutrality in the EU by 2050.

Four scenarios are considered. Scenario assumptions are summarised in Table 1, and further details can be found in supplementary material. Scenarios were finalised in 2021, and do not include representation of more recent policy choices by governments. All scenarios meet the same emissions constraint (a cumulative constraint of 43GtCO₂ from 2020 to 2050) and reach net zero greenhouse gas emissions in 2050.

In this study, we used the PRIMES model to quantify decarbonisation pathways towards net zero based on the narratives in Table 1. These model results are presented in detail in (Rodrigues et al. 2022). PRIMES has been extensively used to quantify energy outlook scenarios for the European Commission (Capros et al. 2016) and to analyse EU energy and climate policies, including the ‘Clean Planet for all’ long-term strategy (European Commission 2018) and the recent Fit for 55 package (European Commission 2021).

The PRIMES model simulates the energy system of all EU Member States and the UK (Anon 2018) to 2050. It provides data for each European country, and it has an annual focus, but represents hourly load and generation variability through the use of multiple typical days and hours per year. PRIMES provides explicit representation of energy system transformation, vehicle adoption by technology, fossil fuel and renewable energy production and a wide range of energy transition pathways. The model provides projections of energy demand by sector (buildings, various passenger and freight transportation segments, 10 industrial sub-sectors), energy transformation and supply (e.g. power generation, refineries, hydrogen production), energy-related investment, CO₂ emissions and energy system costs under alternative policy scenarios up to 2050. It simulates a multi-market equilibrium by calculating energy prices which balance demand and supply in all sectors (Fragkos et al. 2017). The behaviour of each agent (e.g. energy consumers, power producers, industries) is simulated through detailed modelling founded on micro-economics and includes technical, engineering-oriented constraints. For further information about the PRIMES model, please see supplementary material.

5.2 Data on employment in high-carbon industries

The principal data source for identifying regional economic dependence on specific sectors is Eurostat’s regional Structural Business Statistics (Eurostat 2021a). This data source provides industry-by-industry data on employment at the NUTS2 level of spatial disaggregation. However, these records are incomplete at the NUTS2 level, and considerable additional work was required to estimate values that are unavailable or that had been suppressed for confidentiality reasons, including drawing on additional data sources. The procedures used to estimate missing data values for each sector are summarised in the supplementary file.

Table 1 Summary of scenario narratives

Scenario narrative	Brief description	EU + UK fossil fuel production (Mtoe, 2035)	EU + UK final energy demand (Mtoe, 2035)	EU + UK total power generation (TWh, 2035)
New Players and Systems	Focus on end-use/scalable technologies enabling electrification of energy services (electric vehicles, heat pumps) and large-scale expansion of variable renewable energy combined with storage	93	856	4113
Incumbents' Renewal	Focus on supply side change; large-scale technologies (CCS and nuclear); clean syngas allow end users to keep their liquid-/gas-based appliances and the current energy infrastructure	103	874	4078
Efficiency and Sufficiency	Focus on demand savings and change of usage patterns. New lifestyle changes and efficiency measures and related investment, including in building retrofits, circular economy, etc	89	823	3876
Europe of two speeds	Some European countries emerge as leaders, while others are slower to enact aggressive decarbonisation policies. By 2040, all countries are aligned in efforts to achieve an energy system compatible with 1.5°	103	828	4130

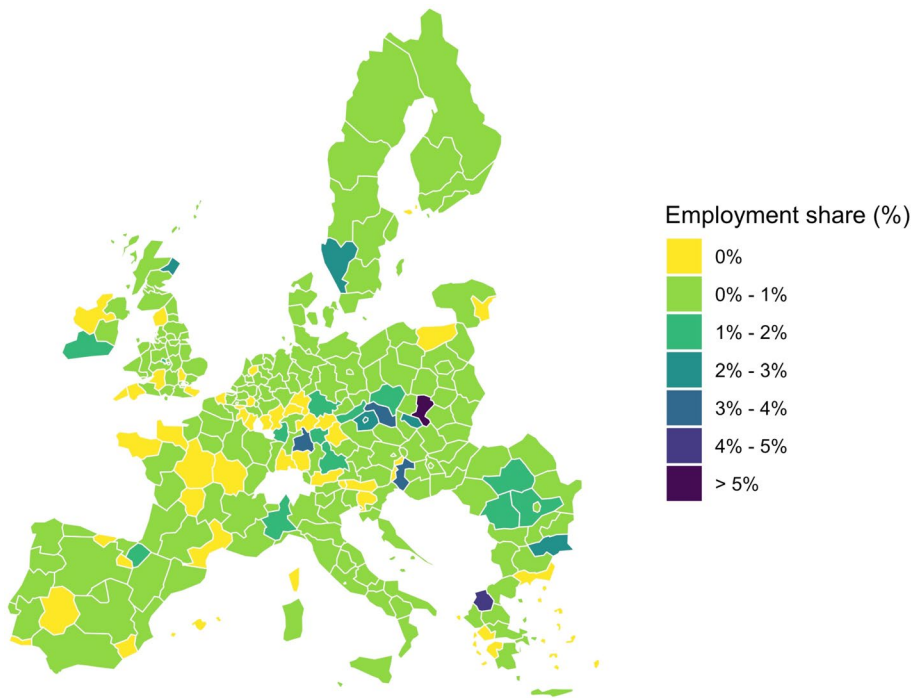


Fig. 1 Share of employment in the high-carbon sectors

For the indicator used in this paper, we used the employment *share* in the high-carbon activities, rather than the absolute number of workers. This is because the populations of NUTS2 regions vary over several orders of magnitude. Using absolute numbers would likely miss smaller regions with high dependence on fossil fuel activities. The resulting map of regions is shown in Fig. 1.

6 Exploring assumptions about industry-specific impacts of job losses

The four industries considered in this study—coal mining, oil and gas extraction, manufacture of internal combustion engines (ICE) and petroleum refining—differ substantially in important characteristics. For example, coal mining and oil extraction are geographically restricted to specific geological conditions, while ICE manufacturing can be relocated to other regions or countries depending on adequate labour skills, infrastructure and capital resources. These differences are important, because the characteristics of different economic activities influence the extent to which dependence on them results in economic vulnerability. New growth paths and emerging industries tend to ‘branch’ out of technologically related industries (Frenken et al. 2007; Neffke et al. 2011). The intuition behind this observation is straightforward: regions are better at incubating new industries that share similar characteristics in terms of technological capabilities, institutional arrangements and skills.

Thus, we can expect that regions with dependence on high-carbon sectors that have close low-carbon technological relatives will be less vulnerable than regions dependent on what one might call ‘black sheep’ industries: those that are not close even to their nearest relatives. For example, the manufacture of internal combustion engines is part of a broader ‘industrial cluster’ (Neffke et al. 2011) which is closely related to several other manufacturing sectors, such as agricultural machinery, cars and machinery parts. Regions heavily dependent on manufacturing internal combustion engines can expect to see those economic activities disappear due to the energy transition, but they are relatively well placed to transition into new, related industrial activities. In contrast, regions dependent on ‘black sheep’ industries (such as coal mining), which have few close relatives, are more vulnerable to decarbonisation.

However, it is not straightforward to assess the degree of relatedness of industries, and the ease with which workers laid off from specific sectors will be re-absorbed into other industries. Observed labour flows are one way of measuring the degree of skill-relatedness of industries, i.e. the extent to which different sectors make use of similar skills. However, such historically observed data are inherently limited. This is partly because observed switches between industries result in measures of skill-relatedness that are predicated on the industrial structure of the observed countries and years. For example, data on skill-relatedness in Germany is unlikely to provide a robust insight into the relative relatedness of workers in the oil and gas industry to other sectors, since Germany has very low employment in this sector and as a result few observed job switches to other sectors. Similarly, historic industrial structure will be of little value in assessing labour flows into sectors that are still emerging or have yet to become established. For example, there has been much speculation and some recent (largely qualitative) analysis of the possible extent of spillovers between offshore oil and gas activities and emerging offshore renewable energy sectors (Mäkitie et al. 2017)—but this has not been captured in industry statistics since these do not disaggregate offshore renewables as a separate sector.

Given these uncertainties, it is not always clear to what extent the different high-carbon industries are unique in the skills on which they depend. In our main analysis (reported in Sections 7.1, 7.2, 7.3), we have assumed that all job losses (in the four sectors) are equal. In order to test the robustness of our resulting regional vulnerability ranking to this assumption, we explore the impact of differentiating skill-relatedness weights by industry. This analysis is presented in Section 7.4. In order to test the impact of differentiating weights based on the characteristics of the four high-carbon industries, we draw on observed inter-industry labour flows in Germany (Neffke et al. 2017) and the Netherlands (Diodato and Weterings 2015). The patterns observed in those studies are broadly intuitive: extractive sectors are relatively less related to other sectors than are manufacturing sectors (such as automotive and ICE manufacturing). This means that coal miners, for example, appear to have skills that are less transferable to other sectors than those working in vehicle manufacturing, implying that coal miners will face correspondingly greater challenges finding employment following lay-offs as a result.

Given the different contexts of these previous studies (one in the German labour market, one in the Dutch), it would not be appropriate to directly use the skill-weights that they observe/estimate in all EU countries, since this would imply a spurious level of accuracy. Rather, we assign weights that reflect the authors’ qualitative judgements about the relative skill-relatedness of these sectors, to test the importance of such assumptions. These judgements are informed by Diodato and Weterings (2015) and Neffke et al. 2017 (e.g. both highlight that coal mining has much lower skill-relatedness to other industries than the other sectors we explore, while refineries and ICE

manufacture have stronger skill-based links to other sectors). We reduce the impact on vulnerability of job losses in ICE manufacturing and refining (assigning a weight of 0.5) and the oil and gas extraction (0.75), while maintaining the impact of job losses in coal mining (which retains a weight of 1).

The exposure measure for each region (r) is calculated as follows, where Emp is the ‘employment share’:

$$Exposure_r = Emp_{r,coal} * 1 + Emp_{r,O\&G} * 0.75 + Emp_{r,ref\&ICE} * 0.5 \quad (5)$$

7 Results

7.1 Most vulnerable regions

Table 2 shows the top ten most vulnerable regions, based on the analysis for 2035. For brevity, the results reported here are for the *New Players* scenario only, but as described in Section 7.2, there is rather little variation across scenarios. From the table, it can be seen that the most vulnerable regions have a high percentage of jobs that are at risk from declining fossil fuel industry activity. It is also clear that this is not the only determinant of vulnerability: for example, Southwest Oltenia has a higher vulnerability rank than North-east Scotland despite having a smaller share of jobs at risk, because it has high sensitivity and low adaptive capacity. Figure 2 shows the regional pattern of vulnerability across all regions for the *New Players* scenario.

7.2 Influence of weight choices on vulnerability outcomes

The results (shown in detail in the supplementary file) reveal that the indicator is sensitive to the chosen weights for exposure, sensitivity and vulnerability. Using equal weights substantially reduces the apparent vulnerability of regions with low unemployment and high innovation potential, such as Western Sweden, Stuttgart and North-eastern Scotland, and increases the vulnerability of regions with high unemployment and/or weak innovation scores (such as Asturias). Five regions remain in the top ten most vulnerable regardless of the weighting scheme. All are in Central and Eastern Europe (Western Macedonia EL53, Silesia PL22, South-eastern Bulgaria BG34, Western Oltenia RO41 and Moravian-Silesia CZ08). The right weighting approach depends on the purpose of the indicator: a higher weight for exposure emphasises the potential impacts of job losses, while equal weights emphasise current regional disparities.

7.3 Variation across deep decarbonisation scenarios

The scenario variation is relatively small in 2035 for the production and processing of fossil fuels, as the four scenarios are based on common climate policy assumptions until 2030, as they achieve the same targets for emission reduction (about 47%), energy efficiency (32.5%) and renewable energy share (32%). All three fossil fuel supply sectors (coal, oil and gas extraction and refineries) see declines of more than 80% by 2035 from 2015 levels. As shown in Fig. 3, this results in rather little variation in the top ten most vulnerable regions across the four decarbonisation scenarios.

Table 2 Top ten most vulnerable regions in the 'New Players' scenario. Each region's NUTS2 code is given in parentheses

Rank	Vulnerability	Major sectors	Share of region's jobs lost in 2035
1	Western Macedonia, Greece (EL53)	Coal mining	4.5%
2	Silesia, Poland (PL22)	Coal mining, ICE manufacture	3.7%
3	SE Bulgaria (BG34)	Coal mining, refineries	1.7%
4	SW Oltenia, Romania (RO41)	Coal mining, ICE manufacture, oil and gas extraction	1.2%
5	Moravian-Silesia, Czech Republic (CZ08)	Coal mining, ICE manufacture	1.7%
6	NE Czech Republic (CZ05)	ICE manufacturing, coal mining, refineries	1.8%
7	NE Scotland (UKM5)	Extraction of oil and gas	1.8%
8	Piemonte, Italy (ITC1)	ICE manufacturing, oil extraction	1.0%
9	NW Czech Republic (CZ04)	Coal mining	1.0%
10	Lower Silesia, Poland (PL51)	ICE manufacturing, coal mining	0.9%

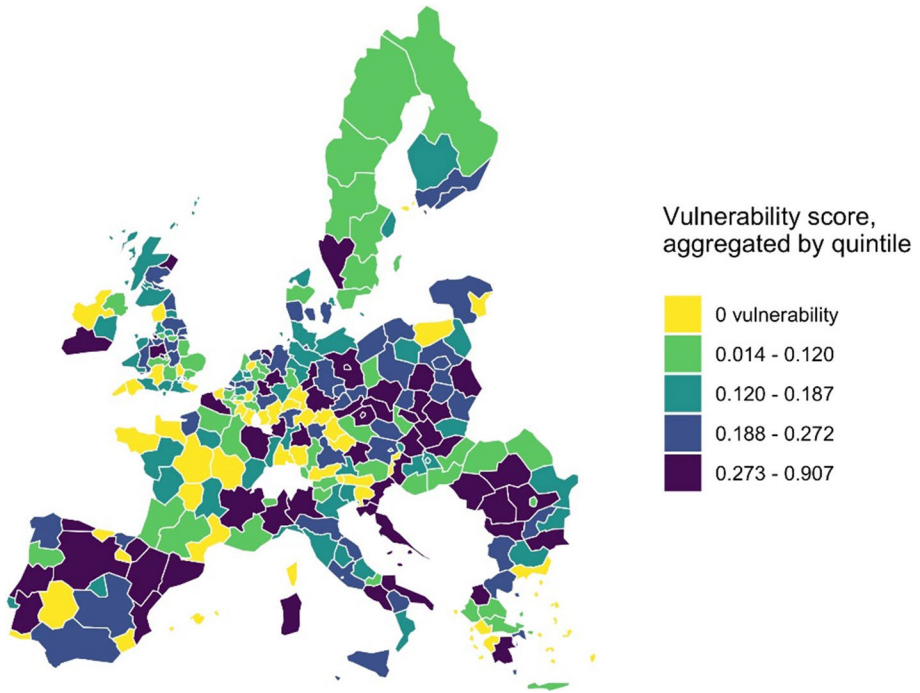


Fig. 2 Vulnerability of regions in the 'New Players' scenario

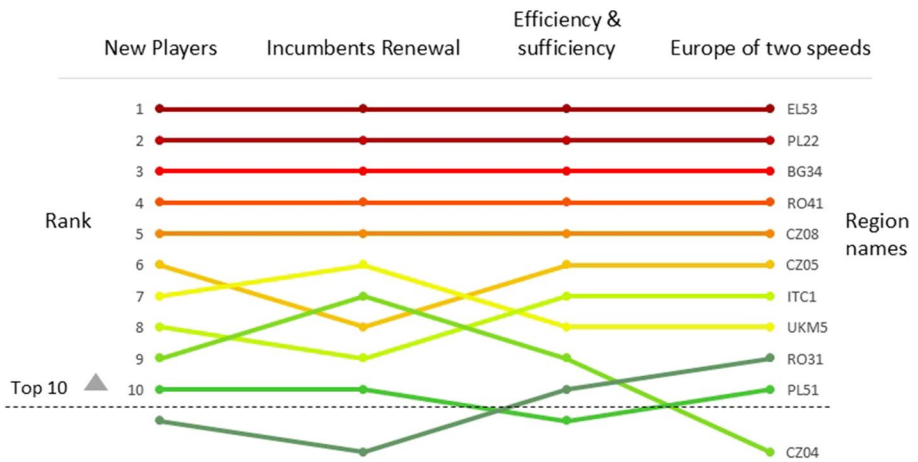
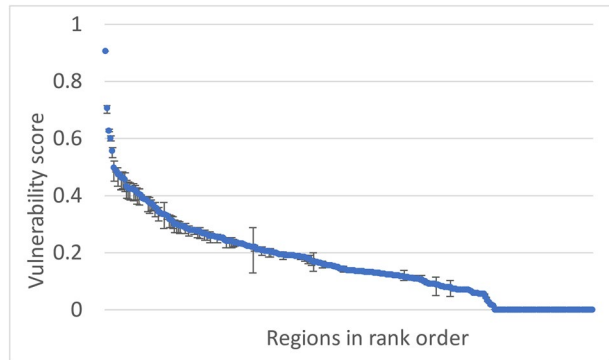


Fig. 3 Changes in rank of the ten most vulnerable regions across scenarios. The figure includes all regions that feature in the top ten most vulnerable in any scenario. Regions are named using standard NUTS2 codes

There is greater scenario variation in the phase-out trajectory of internal combustion engines: in some scenarios, the PRIMES model sees a significant transition role for plug-in hybrids, which support continued manufacturing and use of ICE engine production. The

Fig. 4 The mean score across scenarios for each region ($n=275$), showing the min/max scores across the four scenarios as error bars



changes across decarbonisation scenarios of the relative vulnerability of regions are thus largely driven by differences in internal combustion engine production. For example, the relative vulnerability of the Northeast Czech Republic (CZ05) and Italy's Piemonte region (ITC1) falls in scenarios with a higher deployment of plug-in hybrids and a correspondingly slower decline of manufacturing of engines.

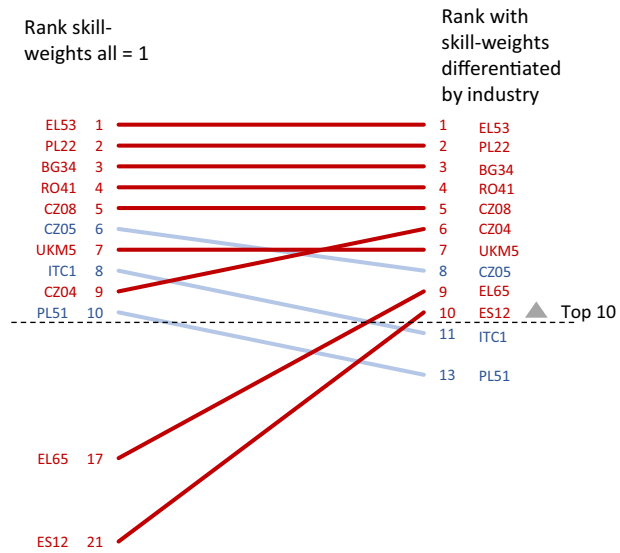
Some oil-producing regions also show larger scenario variation, such as Bulgaria's northwest (BG31) and the Czech Republic's southeast (CZ06). The PRIMES model produces greater variation in oil and gas production by scenario for these countries than for the aggregate level of Europe as a whole.

Figure 4 shows the relative scale of scenario-related variation in vulnerability for each region, in relation to the relative vulnerability of each region across all scenarios. As the figure shows, scenario variation for most regions is small, given that the transition to climate neutrality under all scenarios requires large-scale decline of all fossil-related activities and massive expansion of renewable energy.

This shows that the vulnerability of EU regions mostly depends on the ambition level of the decarbonisation target, and as the target becomes increasingly stringent (e.g. net zero), there are relatively small differences across alternative scenarios at least with regard to the projected phase-out of fossil fuel activities. In contrast, the decarbonisation scenarios show greater variation in the patterns of deployment of clean energy technologies. For example, solar PV and wind power expand more in New Players, while bioenergy is more prominent in the Incumbents scenario. These differences in the growth of clean energy do little to influence the decline in fossil fuels, which is similar across all scenarios. Further discussion of the scenarios, and the differing technology pathways that they represent, can be found in (Rodrigues et al. 2022).

Scenario differences increase after 2040, as different mitigation options are used in each decarbonisation scenario. For example, energy consumption declines more rapidly in the Efficiency and Sufficiency scenario, and the greater variation in technology pathways from 2040 does generate greater variation between scenarios in regional vulnerability. However, even when examining industry declines in 2040, scenario variation has little influence on the top ten most vulnerable regions. The major changes are that regions dominated by internal combustion manufacturing and refineries become relatively more vulnerable, as the transition towards electric vehicles accelerates after 2035. The most vulnerable regions remain highly vulnerable whether one examines declines expected by 2035 or by 2040. See supplementary material for further detail on scenario differences in 2040.

Fig. 5 Change in vulnerability of the top ten most vulnerable regions in the ‘New Players’ scenario, with and without skill-weights. Red regions are those in which more than 50% of high-carbon jobs are in extractive sectors; blue regions are those in which less than 50% of high-carbon jobs are in extractive sectors. Regions are named using standard NUTS2 codes



7.4 Influence of skill-relatedness weights

In Section 6, we described how weights can be differentiated for each industry component of the ‘exposure’ measure (e.g. jobs lost from coal mining), to reflect the fact that, for example, coal miners are likely to have fewer skills that can be readily transferred to other sectors than those working in automotive manufacturing. The weighting approach is described in Eq. 5. The results shown so far used equal weights for all four industries (a weight of 1). Here, we show that changing the weights to the values shown in Eq. 5 to account for the greater skill ‘uniqueness’ of extractive sectors compared to the manufacturing industries has an impact on the relative vulnerability of regions. When skill-weights are differentiated by industry, regions with a preponderance of ICE manufacturing and refining become relatively less vulnerable, leaving those dominated by coal, oil and gas extraction as relatively more vulnerable (see Fig. 5).

The regions whose vulnerability score is most changed by the differentiation of skill-weights across all scenarios are those with high shares of internal combustion manufacture and/or refineries: NE Czech Republic (CZ05), Stuttgart (DE11), Transdanubia (HU22), Piemonte (ITC1) and Western Sweden (SE23). All these regions face reduced vulnerability when skill-weights are differentiated by industry in the analysis. The map showing vulnerability for all regions, when including differentiated skill-weights, is shown in Fig. 6.

Overall, the impact on vulnerability of differentiated skill-relatedness weights is relatively small for most regions. Differentiating skill-weights changes the rank order of regions’ vulnerability. The mean change in vulnerability rank across all regions provides a measure of the variation in vulnerability associated with the change in skill-weights (from equal weights for all industries to weights that are differentiated by industry). In other words, differentiating skill-weights causes changes in rank for many regions, and the magnitude of that set of changes in rank can be expressed as the mean shift in rank. The mean shift in rank associated with adjusting skill-weights by industry is 5.6. Similarly, the mean shift in rank can be used to assess the magnitude of changes associated with variation

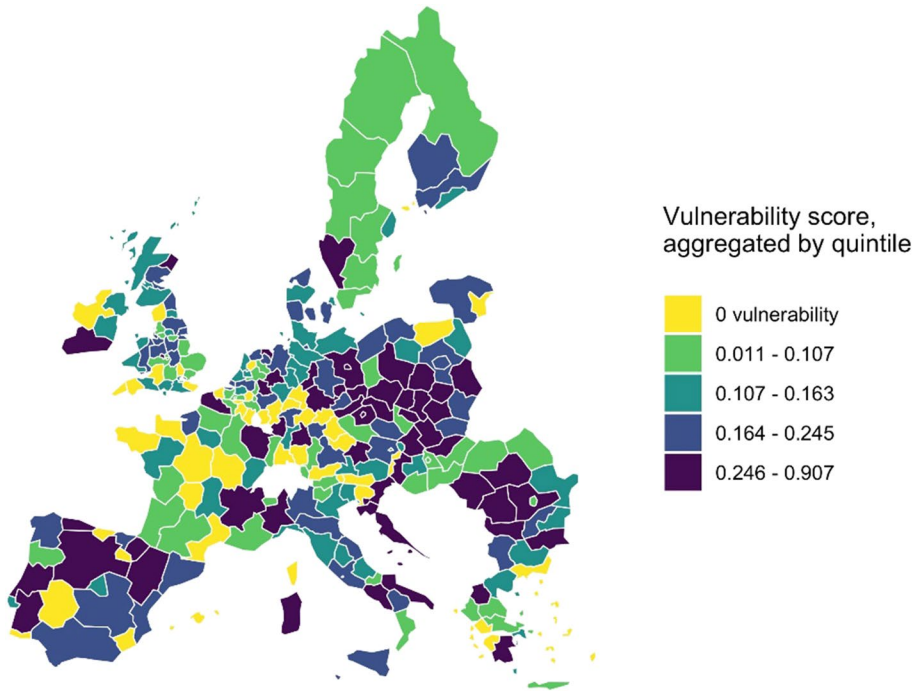


Fig. 6 Regional vulnerability including skill-relatedness weights differentiated by industry in the ‘New Players’ scenario

across scenarios. In contrast with the adjustment of skill-weights, the mean rank shift arising from variation among scenarios is lower (at 3.5).

However, the effect of scenario variation is more skewed than that for skill-weights: with scenario variation, many regions see little or no change in their relative vulnerability, but a small number of regions see substantial shifts in rank. This result highlights that scenario variation generates more regionally concentrated changes, as the model makes choices to, for example, eliminate oil production in a given country. In contrast, the impact of skill-weights results in a more geographically even reduction in relative vulnerability for those with non-coal activities.

8 Conclusions, limitations and further work

Decarbonisation of the EU and UK economies will involve the decline of a wide range of extractive and industrial activities, with associated risks for regions that are highly dependent on those activities. This paper has mapped the regions that are most vulnerable to those changes. Three broad conclusions can be drawn from the work.

First, there is relatively little variation in vulnerability associated with different EU energy transition pathways that achieve net zero emissions by 2050 and are consistent with the 1.5 °C goal of the Paris Agreement. This is largely because the target is so ambitious that there is little room for deviation from a pathway characterised by rapid phase-out of

coal; the large-scale reduction in oil and gas extraction; and the rapid deployment of electric vehicles in the transport sector leading to massive declines in the demand and supply of refined oil products and in ICE manufacturing. Even a pathway that emphasises some continued use of fossil fuels combined with CCS does little to change the picture of regional vulnerability. The scenarios differ more greatly in terms of which clean energy technologies and strategies develop (e.g. variable renewables, bioenergy, energy efficiency).

Second, geography matters. We confirm that the impacts of decarbonisation pathways are unequally distributed across regions in the EU and UK. There are many regions that combine high levels of exposure to declines in multiple high-carbon industries with high levels of current unemployment rates and low levels of adaptive capacity—many of which are in Central and Eastern Europe. These regions are strong candidates for the EU and national government support to facilitate a ‘just transition’, both for welfare reasons and to reduce the likelihood that such regions become political obstacles to decarbonisation by creating strong social and political resistance to the energy transition (Dijkstra et al 2020). Similar patterns of regional concentration are likely to be found elsewhere (see e.g. Snyder 2018 and Raimi 2021).

Third, the vulnerability measurement is sensitive to assumptions about the relative vulnerability associated with job losses in different sectors. This sensitivity was tested using a simple approach to weighting the relative sensitivity of a region to job losses in different sectors, informed by data on the skill-relatedness of those sectors to other lower-carbon activities. Further research, ideally based on following the employment destinations of laid-off workers from high-carbon industries, would be valuable to improve the vulnerability indicator.

There are several other limitations of the current work, all of which present avenues for further research work. In particular:

- Several high-carbon activities are excluded, on the basis that the data was insufficient to accurately map them. In particular, support activities specific to both coal mining and oil and gas extraction are not included, neither are jobs associated with the operation of fossil fuel power plants. More generally, there are some weaknesses in the existing data on employment in high-carbon industries. Filling the gaps in the available datasets required us to make a number of assumptions and simplifications, which could be improved upon in future research.
- The approach overlooks the structure of other industrial sectors in the region, which is also important: the presence of related industries can facilitate a more rapid absorption of laid-off workers (Hane-Weijman et al. 2018), though, where these are connected through direct input–output relationships, this can further exacerbate the impacts of an industry’s decline (Cahen-Fourot et al. 2021). Further work could capture both direct and indirect job impacts through accounting for detailed input–output flows. We also overlook the positioning of regions in international supply and value chains.
- The RIS indicator provides a useful way to assess the adaptive capacity of each region. However, it overlooks some dimensions of adaptive capacity that are likely to be relevant. For example, the quality of infrastructure and the quality of regional and national institutions are an important component of a region’s adaptive capacity. Assessing whether the indicator is sensitive to the inclusion or exclusion of such data would be a relevant additional step. Similarly, the sensitivity indicator could be expanded, by including attributes like income, and measures of marginalisation relevant to the national context (particularly share of racialised minorities). A richer depiction of sensitivity may highlight additionally vulnerable regions that are not prominent based on the indicator used here. The approach to sensitivity adopted by Raimi et al. (2022) appears particularly promising as a future extension to the work presented here.

Achieving decarbonisation is urgent, but the transition creates risks for regions that have been historically reliant on high-carbon industries. EU and national policymakers, regional authorities and commentators have rightly identified the importance of delivering a ‘just transition’. Such efforts rely on tools that enable the identification of regions that are particularly vulnerable to decarbonisation. The vulnerability indicator developed in this paper provides a conceptually straightforward, customisable and flexible approach that can be combined with a variety of decarbonisation scenarios to identify the regions with the highest vulnerability to decarbonisation which may require support to change their economic paradigms away from fossil activities, re-skill workers from declining sectors and re-orient their economies towards new, sustainable activities.

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Author contribution Conceptualisation: WM; PRIMES modelling: PF; data collection: WM and TR; data analysis: WM and TR; writing—original draft: WM; writing—review and editing: WM, MM, TR, PF and JC; visualisation: JC; funding acquisition: WM and PF.

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Data availability The data used in this study are mostly available from the public sources cited in the text or can be found in the supplementary online material. Additional data requests can be made to the authors.

Declarations

Ethical approval The project was given ethical approval by the Research Ethics Committee of UCL’s Bartlett School of Environment, Energy and Resources.

Participant consent and consent for publication The scenarios used in the project were developed through a co-design process. Informed consent was obtained from all participants, including consent for the resulting work to be published.

Conflict of interest The authors declare no competing interests.

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