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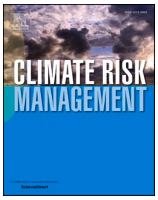

Creating quantitative scenario projections for the UK shared socioeconomic pathways

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ABSTRACT

The Shared Socioeconomic Pathways (SSPs) were developed as a framework for exploring alternative futures with challenges for climate change mitigation and adaptation. Whilst originally developed at the global scale, the SSPs have been increasingly interpreted at the national scale in order to inform national level climate change policy and impact assessments, including mitigation and adaptation actions. Here, we present a set of quantitative SSP scenario projections, based on narratives and semi-quantitative trends, for the UK (the UK-SSPs) for a wide range of sectors that are relevant to the UK climate research, policy and business communities. We show that a mixed-methods approach that combines computational modelling with an interpretation of stakeholder storylines and empirical data is an effective way of generating a comprehensive range of quantitative indicators across sectors and geographic areas in a specific national context. The global SSP assumptions of low challenges to climate adaptation lead to similar socioeconomic outcomes in UK-SSP1 and UK-SSP5, although based on very different dynamics and underlying drivers. Convergence was also identified in indicators related to more efficient natural resource use in the scenarios with low challenges to climate change mitigation (UK-SSP1 and UK-SSP4). Alternatively, societal inequality played a strong role in scenarios with high challenges to adaptation leading to convergence in indicator trends (UK-SSP3 and UK-SSP4).

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1. Introduction

Societal change may have a greater impact on the future of human and environmental wellbeing than climatic change (Dunford et al., 2015), although these effects are not mutually exclusive. In order to examine vulnerabilities, costs, and consequences of different potential futures, it is therefore important to account for uncertainties about societal change in a systematic way and to create internally consistent scenario datasets that reflect these changes. Such scenarios can then be used to frame various modelling exercises, for example, in the quantification of land use, demography and impacts on the energy sector, food system or nature. Exploring potential future societal conditions has been the subject of decades of scenario development work across a large range of disciplines (Rounsevell et al., 2021; Rounsevell & Metzger, 2010). For climate change applications, the Shared Socioeconomic Pathways (SSPs) are the most recent and widely used set of global socioeconomic scenarios, especially within the context of the assessment reports of the Intergovernmental Panel on Climate Change (IPCC) (O'Neill et al., 2020).

In their basic form, the SSPs describe five, alternative socioeconomic futures until 2100 (O'Neill et al., 2017) framed according to challenges to climate change mitigation and adaptation (O'Neill et al., 2014). The SSPs can be combined with the Representative Concentration Pathways (RCPs) of climate forcing, and the Shared climate Policy Assumptions (SPAs), to create integrated scenarios that can be applied to impact models for the assessment of specific opportunities, obstacles, costs and consequences in different futures (Kriegler et al., 2014; van Vuuren et al., 2014).

The global SSPs consist of qualitative storylines and quantitative projections covering demographic, economic, institutional, cultural, political, technological, and lifestyle related features and drivers of societal change. They also incorporate the state of ecosystems that are affected by human activity, although without making assumptions about climate change impacts (O'Neill et al., 2014). Quantitative SSP projections have been created for specific indicators, for example, population (KC & Lutz, 2017), incomes (Crespo Cuaresma, 2017), and energy (Riahi et al., 2017). These quantified projections are hosted within the International Institute for Applied Systems Analysis (IIASA) Public SSP Database (https://tntcat.iiasa.ac.at/SspDb) and are commonly used as inputs to climate change impact assessment at multiple scales.

By design, the global-scale *basic* SSPs are generic scenarios, which need to be *extended* to be relevant in specific national, local, or sectoral contexts (O'Neill et al., 2014). Different types of both qualitative and quantitative SSP extensions are possible, i.e., by a) increasing spatial resolution to create more local specificity, b) increasing temporal resolution to define more dynamic specificity, and c) increasing thematic resolution to cover a larger range of socioeconomic sectors and indicators.

Many studies have generated extended SSPs (O'Neill et al., 2020). Some recent examples of regional extensions include the Barents region (Nilsson et al., 2017), the Baltic Sea (Zandersen et al., 2019), Finland (Lehtonen et al., 2021), the UK (Harmáčková et al., 2022; Pedde et al., 2021) and Europe (Kok et al., 2019; Mitter et al., 2020). Most of these studies have used participatory approaches to

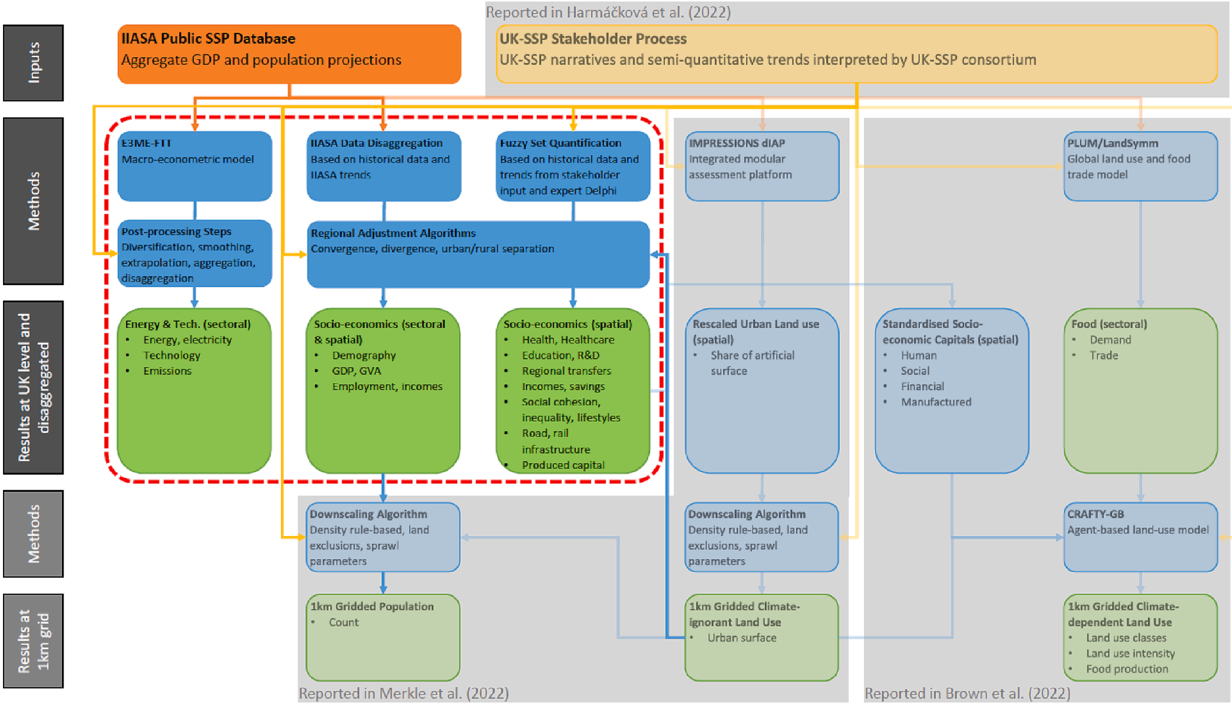

Fig. 1. UK-SSP Quantification Process. Global SSP inputs in orange, UK-SSP narratives and semi-quantitative trends inputs in yellow, models, methods, and model-internal variables in blue, quantified UK-SSP indicators in green. Components covered in this paper are encircled in red, components covered in other UK-SSP papers are greyed out.

incorporate locally-relevant stakeholder knowledge into qualitative narratives and semi-quantitative trends. Quantitative SSP extensions have been created for the U.S. Southeast (Absar & Preston, 2015), and for West Africa (Palazzo et al., 2017), mostly focusing on a narrow range of indicators for one specific sector.

Climate policies are generally developed at the national level and implemented sub-nationally. Such policies need to be developed in a holistic way that takes into account synergies, trade-offs, and potential unintended consequences across sectors and scales (e.g. Boyle et al., 2021). This requires downscaled scenario projections that take account of locally- and sectorally-specific context, and that cover a large range of sectors at an appropriate spatial resolution. Several studies have identified the research need of bridging across different methods (top-down and bottom-up), different data types (qualitative and quantitative), and different spatial scales in the context of the SSPs (Birkmann et al., 2015; Rothman et al., 2014; Star et al., 2016). However, no extension has yet generated a wide range of quantitative projections at high spatial resolution that represent the unique characteristics of a given region across a range of sectors, whilst being consistent with both the basic SSPs and detailed national SSP storylines developed within a participatory process.

In this article, we present a comprehensive set of quantitative SSP projections that were developed at the national to sub-national scale for the UK. The UK-specifics of the pathways, and the stakeholder process that underpinned them, are described with detailed narratives and semi-quantitative trends in Pedde et al. (2021) and Harmáčková et al. (2022). We build upon this work, using a mixed-methods approach of different models and data to integrate the needs and considerations of a wide range of stakeholders from research, policy and business sectors.

2. Methodology

2.1. General approach

We applied a mixed-methods approach to quantitative scenario development combining participatory stakeholder input, empirical data, and several different computational modelling and methodological approaches to create disaggregated future projections of socioeconomic change for climate change impact assessment in the UK. We used a standardised process to translate and downscale qualitative UK-SSP data (Harmáčková et al., 2022) and the global SSP database in the creation of future projections for 29 indicators (Fig. 1). This paper reports on 22 of these indicators, which are climate-independent and do not go beyond a spatial resolution of local authority districts. Detailed methodology and results for generating 1 km resolution urbanisation, population and climate-dependent land use indicators are reported in Merkle et al. (2022) and Brown et al. (2022) respectively. The quantitative projections were created for decadal time steps from 2020 to 2100.

The full quantification process-flow is visualised in Fig. 1. Through two workshops and several user panels, we engaged with UK stakeholders from the climate change research, policy, and business communities to extend the global SSP narratives, create semi-quantitative trends for key drivers and system diagrams of driver interactions (Harmáčková et al., 2022). The same participatory events were used to define which indicators should be quantified and at what spatial, temporal and thematic resolutions, given availability of historical data. We started with a longlist of potential indicators, which were then prioritised by stakeholders. With the exception of land use (Brown et al., 2022), indicators that are climate-dependent were excluded, in order to focus on the socioeconomic changes that are contingent on the SSPs. The final set of indicators included all stakeholder 'must haves', most stakeholder 'desirables', and some additional indicators such as produced capital, which were needed as inputs to the land use modelling (Brown et al., 2022).

The quantification of indicators reported here was carried out using three types of methods: (i) macro-econometric modelling; (ii) the disaggregation of projection trends from the IIASA database; and (iii) stakeholder-led, semi-quantitative fuzzy sets that were adjusted for regionally specific changes according to the UK-SSP narratives. Consistency across indicators was ensured by parameterising models according to the UK-SSP narratives and semi-quantitative trends (Harmáčková et al., 2022), and by linking models together where necessary. All indicators were quantified in an iterative process, whereby results were reviewed and revised at least two times within the wider project team and in the stakeholder participation formats. A training workshop at the end of project was conducted to familiarise stakeholders with the results, and how to apply the scenarios in practice.

2.2. Quantification using macro-econometric simulation modelling

The macroeconomic model E3ME-FTT was used to create the projections for energy, electricity, technology and CO_2 emissions. The economic model was extended with environmental, technological, and energy components comparable to Palazzo et al. (2017), although without being bound by the same neoclassical assumptions. E3ME-FTT is a post-Keynesian macro-econometric model, allowing for imperfect price adjustments, non-equilibria markets and limited rationality of economic actors (Mercure et al., 2018). Electricity and technology were disaggregated by sector, while energy and emissions were kept as aggregates. Parameterisations and post-processing steps (diversification, smoothing, extrapolation, aggregation and disaggregation) were done in an iterative process to ensure consistency. Further details are given in SM.2.

2.3. Quantification using disaggregation from the IIASA database

Population size, demography and GDP were derived directly from the global SSP database (Crespo Cuaresma, 2017; KC & Lutz, 2017) and interpolated to fit recent historical UK data. While GDP was kept as an aggregate indicator, population and demography were spatially disaggregated using a similar method to Terama et al. (2019) and Absar & Preston (2015), i.e. by using historical data at local administrative units to derive proportions of individual areas and then imposing the aggregate national trend on these. The disaggregated baseline was created from the UK Office for National Statistics (ONS) data, available at the level of Local Authority Districts (LAD). The proportions of population across LADs are allowed to change over time, following urbanisation patterns described in Merkle et al. (2022). Details are provided in SM.3 and SM.5. We report how population was further downscaled to the 1 km grid in Merkle et al. (2022). Scaling methods were used to generate projections of GVA, household incomes, and employment. Spatially disaggregated versions of these indicators were created per capita, in order to account for size differences between the local areas. Further details are given in SM.3.

2.4. *Quantification using stakeholder-led fuzzy sets*

All other indicators, including education and health, were projected building on the fuzzy sets approach developed by Dunford et al. (2015a), Pedde et al. (2018), and Tinch et al. (2015). As in these earlier studies, we applied an iterative process based on interpretation of stakeholder's semi-quantitative trends (Harmáčková et al., 2022). Baselines were created from spatially disaggregated historical data from official sources, such as ONS, Eurostat and the UK Household Longitudinal Study (UKHLS). Projection trends were created by applying expert interpretations of the semi-quantitative trends to the spatially disaggregated historical data. Unlike previous studies using fuzzy sets, we set thresholds and minimum and maximum limiting values for each indicator with reference to European and worldwide empirical data to inform and constrain the expert interpretations of the semi-quantitative trends. The process was conducted through an internal Delphi process, in order to further minimise subjectivity. A significant advantage of the stakeholder-led fuzzy-set method over other indicator-based approaches that assume fixed relationships to GDP (e.g. Acosta et al., 2013) is that socioeconomic decoupling from traditional indicators of economic welfare is possible where narratives suggest so (Tinch et al., 2015). Further details are given in SM.4.

2.5. *Regional adjustments*

All spatially disaggregated projections were adjusted for specific regional developments, interpreted from the UK-SSP narratives. These included geographic adjustments between the countries and regions of the UK, but also between rural and urban areas. We applied three different kinds of geographic adjustments, namely linear convergence, linear divergence, and separation of rural and urban areas. Linear convergence implies that quantitative differences between areas decrease over time. Linear divergence implies that differences between areas increase over time. Rural/urban separation implies that either rural areas or urban areas have a modified projection trend (between 100 % higher and 100 % lower of the original trend). Urban and rural areas were defined according to density of urban land use, based on the UK-SSP urbanisation scenarios reported in Merkle et al. (2022). Further details are given in SM 5.

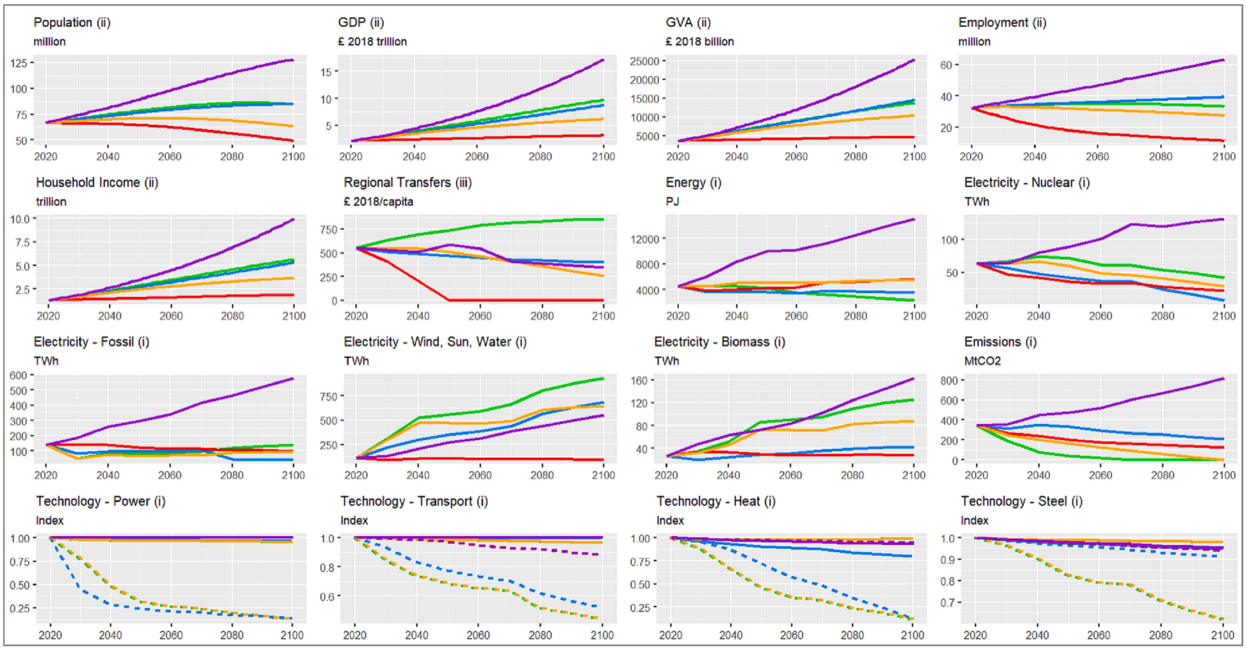

Fig. 2. Quantified indicators at the aggregate level and at the sectorally disaggregate level. UK-SSP1 in green, UK-SSP2 in blue, UK-SSP3 in red, UK-SSP4 in orange, UK-SSP5 in purple. Methods in brackets, (i) E3ME-FTT, (ii) IIASA-based, (iii), stakeholder fuzzy sets based. In the technology index plots located in the bottom row, solid lines represent high carbon technology and dashed lines represent low carbon technology.

3. Results

The quantified UK-SSP indicators together describe spatially and sectorally disaggregated future projections until 2100, consistent with the qualitative UK-SSP narratives for the UK (Harmáčková et al., 2022). All indicators quantified at aggregate and sectorally disaggregate levels are given in Fig. 2, while indicators quantified at spatially disaggregate levels are given in Fig. 3. Several example maps for spatially disaggregated indicators are given in Figs. 4 – 7. The entirety of line graphs and spatial maps of the quantified indicators (more than 140 figures) are openly accessible through Insight Maker interfaces on the UK Climate Resilience Programme website (https://www.ukclimateresilience.org/products-of-the-uk-ssps-project/). A full dataset of all indicators is also available on the same website.

The general picture provided by the quantified UK-SSPs is as follows. UK-SSP1 and UK-SSP5 show similarly high socioeconomic outcomes, which are evenly distributed across the UK population, even though these two scenarios are based on very different assumptions about the dynamics and drivers of socioeconomic change (Figs. 2 and 3). UK-SSP4 and UK-SSP3 yield the lowest socioeconomic levels for the largest part of the population (Figs. 2 and 3). UK-SSP2 sits in the middle between the high and low scenarios (Figs. 2 and 3), as might be expected for a ‘middle of the road’ scenario. Low carbon technology becomes cheaper in all scenarios, although the greatest cost reductions are achieved in UK-SSP1, UK-SSP2 and UK-SSP4 (Fig. 2). The following paragraphs are structured according to general similarities and differences between the scenarios. We provide examples for how the quantitative indicators represent the UK-SSP narratives, starting with UK-SSP1 and UK-SSP5, moving on to UK-SSP3 and UK-SSP4, and ending with the middle of the road scenario UK-SSP2. Some methodological reflections are provided in the subsequent discussion section.

Across indicators we generally find improvement in the socioeconomic indicators for both UK-SSP1 and UK-SSP5. Median tertiary education levels across areas increase from 41 % to 71 % in UK-SSP1 and to 66 % in UK-SSP5 by 2100 (Figs. 3 and 4). Median life expectancy levels across areas increase from 81 to 100 years in UK-SSP1 and to 105 years in UK-SSP5 (Fig. 3). These developments are accompanied by increases in public services, e.g. 98 % more GPs per capita across areas in UK-SSP1 and 157 % more GPs per capita across areas in UK-SSP5 (Fig. 3). A further similarity between socioeconomic indicators in UK-SSP1 and UK-SSP5 is that inter-regional differences are reduced over time, as both scenarios assume strong convergence across regions due to decreases in regional inequalities. Fig. 3 illustrates this convergence across indicators, as data ranges in UK-SSP1 and UK-SSP5 decrease in most cases. Fig. 4 illustrates convergence in the case of education. As shown in this case, education levels increase substantially faster in northern England than in the London area.

While socioeconomic development is high in both UK-SSP1 and UK-SSP5, the underlying causes of this development are very different. In UK-SSP5 the main driver is economic growth through massive material extraction and cheap fossil fuels such as shale gas (Harmáčková et al., 2022). GDP levels in UK-SSP5 increase nearly eightfold and population almost doubles, while primary energy supply more than triples to accommodate demand (Fig. 2). Electricity generation from fossil fuels increases from 160 to 576 GWh and

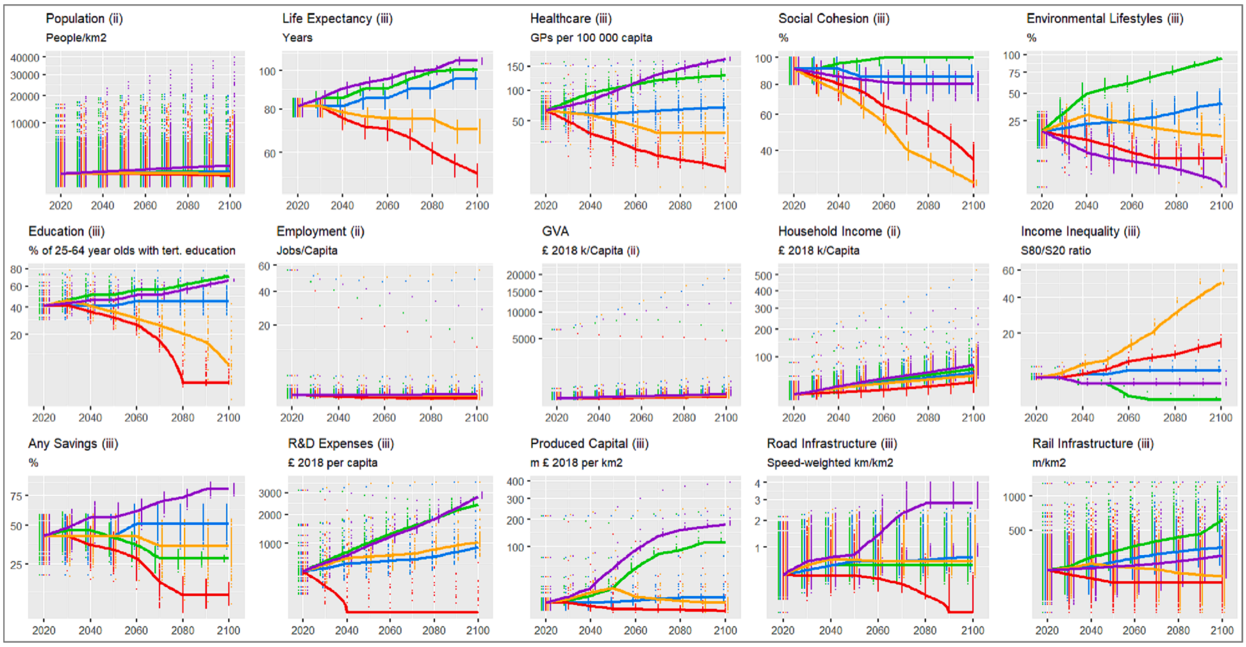

Fig. 3. Quantified indicators for the UK that have been spatially disaggregated, showing the range of sub-national values. Ordinate axes are square root transformed. Trend lines connect the median values for each scenario. UK-SSP1 in green, UK-SSP2 in blue, UK-SSP3 in red, UK-SSP4 in orange, UK-SSP5 in purple. Methods in brackets, (i) E3ME-FTT, (ii) IIASA-based, (iii), stakeholder fuzzy sets based. Vertical lines and dots capture the distribution across sub-national areas at each time step. Increasing vertical extents imply divergence over time (e.g. Education, UK-SSP4), decreasing vertical extents imply convergence over time (e.g. Environmental Lifestyles, UK-SSP1).

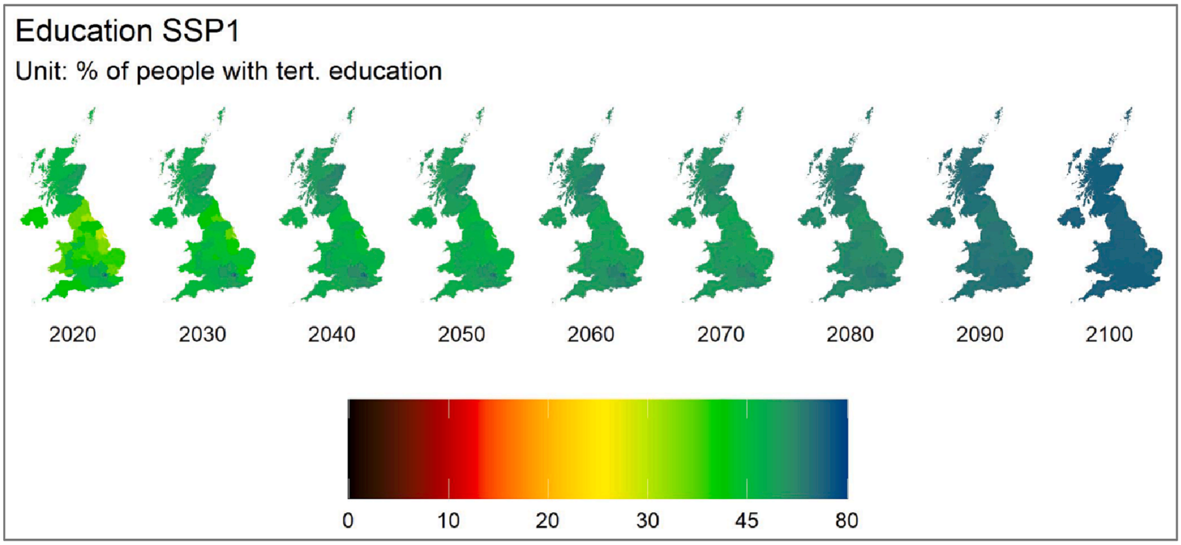

Fig. 4. Tertiary education levels across areas in UK-SSP1. The maps show an increasing trend as well as convergence across areas. The colour legend is chosen to reveal categorical bands from very low (black to red) to very high (green to blue).

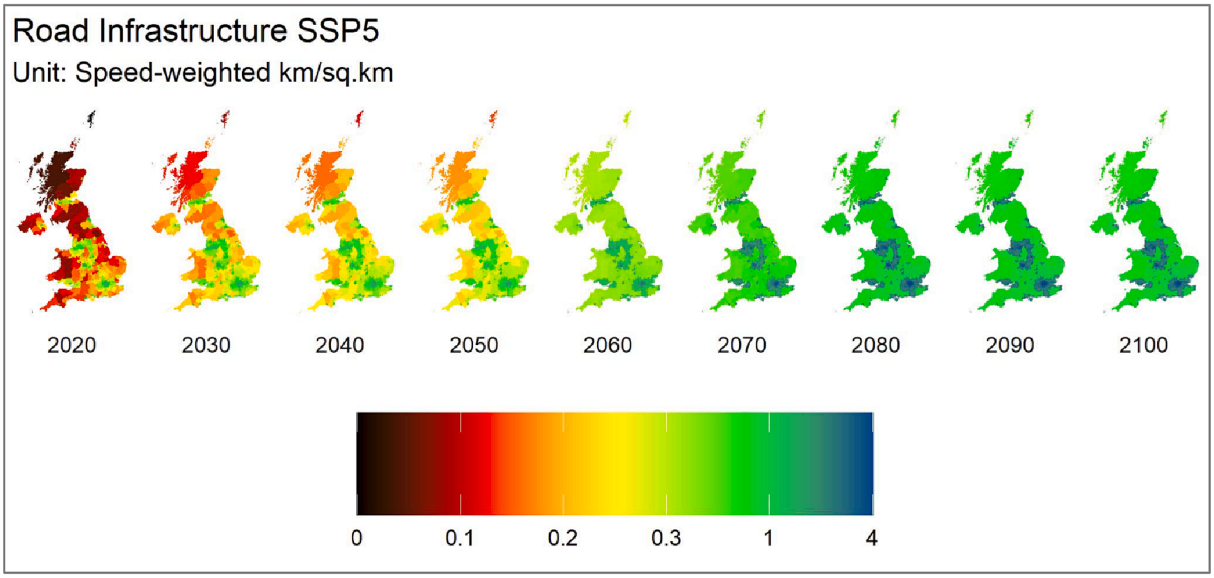

Fig. 5. Road Infrastructure in UK-SSP5. The maps show an increasing trend, while rural areas' increase is slightly lower than the increase observed in urban areas.

this fossil-fuel dependence along with highly materialistic lifestyles leads to a 139 % increase in industrial CO_2 emissions between 2020 and 2100 (Fig. 2). International climate agreements are ignored in this scenario (Harmáčková et al., 2022). It is important to note that as stipulated in the formulation of the SSPs, SSP5 does not include the impacts of climate change that might be expected in a high emissions world.

Conversely, in UK-SSP1, population levels only increase by 27 %, and nearly 95 % of the population adopt environmental lifestyles (Figs. 2 and 3). UK-SSP1 is the greenest scenario, based on a public view that standards of living and jobs are associated with a healthy state of the natural environment (Harmáčková et al., 2022). Electricity needs are largely covered by regenerative sources, and industrial CO_2 emissions reach net zero by 2070 (Fig. 2). UK-SSP1 is a collaborative and egalitarian scenario, where access to public services and standards of living are high, although without being based on a high material footprint. Monetary values are less important (Harmáčková et al., 2022), and so average savings slightly decrease, while income levels are distributed more evenly and social cohesion climbs to the highest level compared to all other scenarios (Fig. 3).

Although produced capital in both UK-SSP1 and UK-SSP5 converge to high levels between £111 million per km^2 (in the Scottish

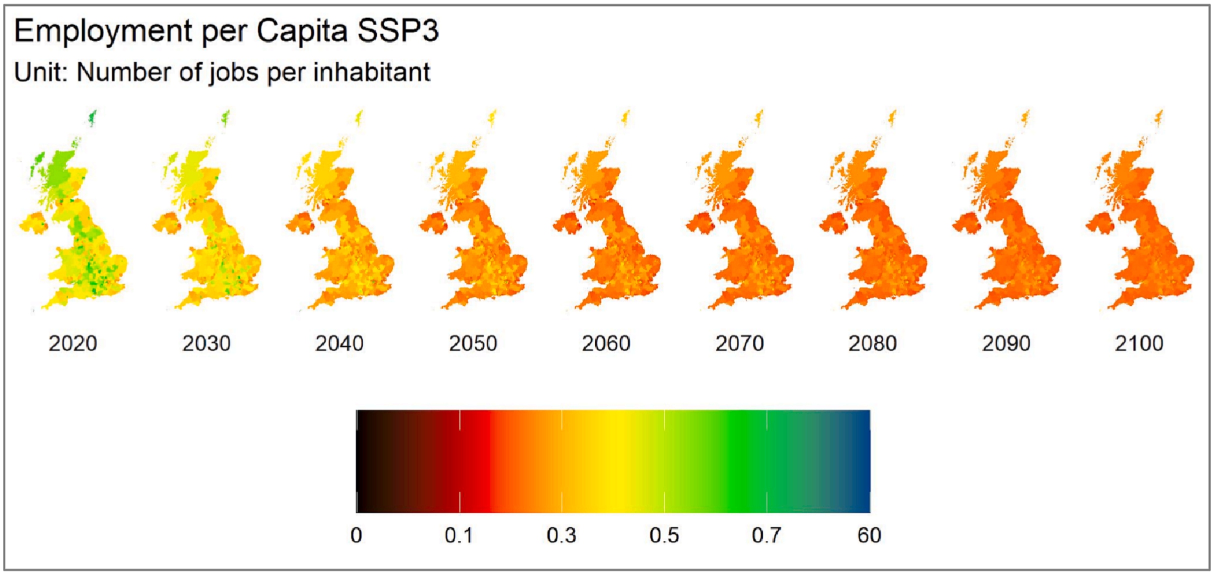

Fig. 6. Employment per capita across areas in UK-SSP3. The maps show a decreasing trend as well as convergence across areas.

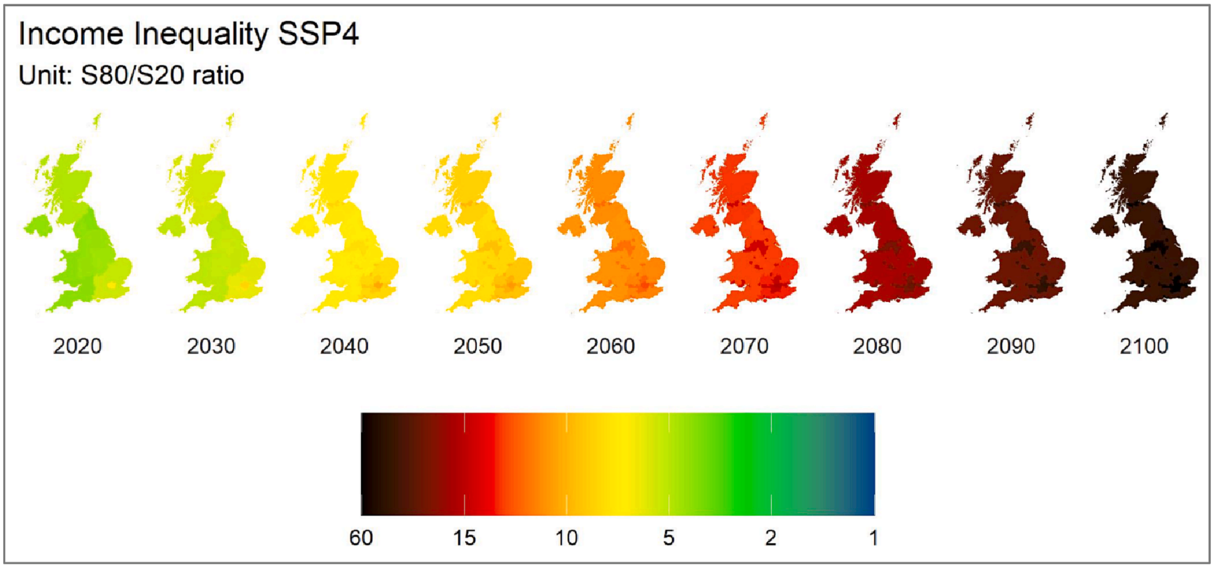

Fig. 7. Income inequality across areas in UK-SSP4. The maps show an increasing trend, which is even higher in urban areas than in rural areas. The colour legend is chosen to reveal categorical bands from very low (black to red) to very high (green to blue).

Highlands and Islands, UK-SSP1) and £392 million per km^2 (in London, UK-SSP5), priority sectors for public spending on infrastructure are very different (Fig. 3). Median road infrastructure in UK-SSP5 increases by 755 % (Figs. 3 and 5), accommodating the highly individualistic nature of transport in this scenario (Harmáčková et al., 2022). In UK-SSP1, median road infrastructure only increases by 57 % but rail infrastructure increases by 383 %, reaching the highest rail infrastructure levels compared to all other scenarios (length of railway tracks per km^2 range between 479 m in the Scottish Islands and 1250 m in London) (Fig. 3).

Both UK-SSP3 and UK-SSP4 have generally decreasing socioeconomic trends, with low levels of social cohesion and low standards of living for most of the UK population. UK-SSP3 is a scenario of societal and governmental collapse, leading to widespread job losses and subsistence-living by the end of the century. While the informal economy grows, parts of the formal economy break down and public spending is suspended, leading to a decay in infrastructure and the health system (Harmáčková et al., 2022). Median life expectancy across areas decreases to 51 years and the number of GPs per 100,000 capita decreases from 65 to 7 by 2100 (Fig. 3). Employment levels decrease substantially across the UK and tertiary education levels decrease to a median of 1 % (Figs. 3 and 6). While the socioeconomic collapse implies some emission reductions, energy sources and technologies remain traditional, and fossil-fuel based (Fig. 2).

UK-SSP4 sees a greening of the energy sector, owned by a few members of the societal elite (Harmáčková et al., 2022). It is a scenario in which the elite are well off, but average socioeconomic welfare levels are low, due to extreme inequality (Fig. 3). While the top quintile has 5 times more income than the bottom quintile in 2020, this increases to a level where the top quintile has 50 times more income than the bottom quintile in 2100 (Figs. 3 and 7). Social cohesion is reduced from a median of 91 % to 25 % across areas, and access to education and jobs is highly dependent on where people live and the social class to which they belong (Fig. 3). Increasing inequality across regions is implemented by applying divergence in some indicators such as education (Fig. 3, increasing data ranges over time). Being a scenario of high technological development driven by multinational tech businesses and investments in green energy (Harmáčková et al., 2022), CO_2 emissions reach zero in 2100, but only a 15 % fraction of the population across areas consciously adopt environmentally friendly lifestyles (Fig. 3). The share of renewables for electricity generation increases from 45 % to 85 % (Fig. 2).

UK-SSP2 is the middle of the road scenario and is positioned in the scenario space between UK-SSP1 and UK-SSP3. Many socioeconomic indicators remain at a similar level as today; some socioeconomic indicators increase slightly, although they do not reach the levels of UK-SSP1 or UK-SSP5. Population growth follows a similar trend to UK-SSP1, but UK-SSP2 continues to rely on fossil fuels, and is therefore the second highest emission scenario after UK-SSP5. Industrial CO_2 emissions are slightly reduced from 343 Mt in 2020 to 206 Mt in 2100, but they do not reach net zero (see Fig. 2). As regional inequalities persist according to the narrative (Harmáčková et al., 2022), no spatial convergence or divergence is applied. Inequalities within regions slightly increase and social cohesion levels are slightly reduced, while median tertiary education levels only increase slightly from 41 to 45 %.

4. Discussion

The quantitative projections for the UK-SSPs were created in order to connect the qualitative elements from Pedde et al. (2021) and Harmáčková et al. (2022) with quantitative climate change impact assessments. Covering a wide range of indicators ensures that these assessments are not restricted to single specific sectors or areas, and users are able to make their own judgment about which indicators are useful to them. The quantitative UK-SSP projections are not forecasts, and no probability is associated with any of the five scenarios. Instead, they are fictional, but plausible scenarios, which can serve both analytical and normative functions (Birkmann et al., 2015). The analytical function is that future socioeconomic conditions in the UK can help analysts explore uncertainty around the challenges to mitigation and adaptation in different UK sectors and geographic areas. The normative function is that they can inform debate on desirable and undesirable futures.

Quantifying socioeconomic challenges to climate change adaptation and mitigation is challenging, because it involves a wide range of variables that are rarely quantified (Rothman et al., 2014). No single integrated and spatially explicit computational model exists that covers all the indicators considered here, at the required spatial and temporal resolution. To address this challenge, we applied a mixed-methods approach including different models, while taking particular care to ensure consistency of the projections. Extending, disaggregating and downscaling SSP data that are usable for climate research needs to comply with three consistency criteria, namely consistency with existing local scale data, with global scale data, and internal consistency provided through a transparent methodology (van Vuuren et al., 2010). Within the UK-SSP project, consistency with existing local scale data was ensured by basing all projections on sectorally or spatially disaggregated empirical data, provided by official sources such as ONS and Eurostat. For the other two types of consistency we follow Mitter et al. (2020) in differentiating between vertical consistency (consistency between the global scale and the local scale) and horizontal consistency (internal consistency within the scenario).

4.1. Vertical consistency

Vertical consistency, also called consistency across scales, in scenario modelling is achieved by fixing boundary conditions (Zurek & Henrichs, 2007). Our approach followed the standard way of creating regional or sectoral extensions of the SSPs by defining narratives, sketching trends, and then quantifying indicators that are required in quantitative form (O'Neill et al., 2014). Extended SSPs can use the basic global SSPs as boundary conditions (O'Neill et al., 2014). Accordingly, the global SSP narratives were taken as boundary conditions for creating the extended UK-SSP narratives by Pedde et al. (2021) and Harmáčková et al. (2022). In a similar way, we used the IIASA SSP projections for population and GDP as boundary conditions for the disaggregated quantitative UK-SSP projections, in order to ensure vertical consistency. Using the IIASA data as boundary conditions for generating extended quantitative SSP projections was also done by Absar & Preston (2015), for example.

While vertical consistency ensures that regional studies are connected to one another and with the global framework, it imposes limits to how closely local stakeholder input can be followed. We found significant discrepancies between e.g. GDP growth as considered plausible by the UK stakeholders and as projected by the models included in the IIASA database. Following IIASA projections, UK GDP and thus also incomes increase in UK-SSP3, while stakeholders expected them to decrease. We observed similar discrepancies for UK-SSP1, and agree with the assessment of O'Neill et al. (2017), who argue that SSP1 could well be imagined with less economic and energy growth. Therefore, there is a clear trade-off to be recognised when ensuring vertical consistency with global model outputs, while trying to follow the expert knowledge, views and priorities of local stakeholders. By ensuring consistency with IIASA GDP and population projections for the UK, some quantitative UK-SSP elements became locked into the assumptions made by modellers of the global SSPs, which may or may not be salient for the UK context. In discussions with stakeholders during the UK-SSP user panel meetings, this trade-off was understood and accepted so that UK research and policy could be positioned within consistent global scenario studies. It is recognised, however, that this could be considered a limitation of the study.

4.2. Horizontal consistency

Horizontal consistency, also called internal consistency, in scenario quantification is often ensured by rigid and formalised coupling of different variables within a computational model. Within the UK-SSP project, this strong coupling was not possible for every variable because a) the user community desired a wide range of quantitative indicators for which sectoral models do not exist and b) whether and how there is a relationship between two variables depends very much on the UK-SSP scenario in question. This challenge became clear during the stakeholder process, where system diagrams were created for each UK-SSP to capture the main interdependencies between indicators (Harmáčková et al., 2022). While the same indicators (nodes) were used for each scenario, links between them varied by UK-SSP, and thus no single system model would be able to capture all of the interactions across the UK-SSPs. For example, while GDP is an important predictor for socioeconomic welfare in UK-SSP5, it is less so in UK-SSP1 due to a shift to a wellbeing economy. Therefore, a single integrated model, designed according to dominant social and economic theory and calibrated on the basis of historical data, may not accurately behave in accordance with the futures described in the UK-SSP narratives. It may well be that to truly represent the different UK-SSP worlds, which are logically and structurally very different from one another, five different spatially and sectorally explicit models would be needed to reflect the storyline's indicators in a scenario consistent manner. However, this would entail quite a paradigm shift in the scenario modelling community, where traditionally projections are generated by perturbation of the input parameters, for a model that otherwise has an identical internal structure rather than adapting the structure itself to match the scenario. The uncertainties associated with this assumption about static model structures representing dynamic and widely differing future worlds have not been investigated (Rounsevell et al., 2021). In order to tell different stories, models need to be reframed to represent stories differently.

Given the need for vertical consistency with the global SSP GDP and population projections, the wide range of socioeconomic variables to be quantified, and various required spatial and sectoral resolutions, the UK-SSP consortium decided to employ a hybrid approach bridging different methodologies and models as required for each variable. We were thereby able to accommodate a much wider range of worldviews and stakeholder opinions embedded within the storylines by combining researcher-driven and stakeholder-driven methods for developing climate risk scenarios as recommended by Star et al. (2016). Process-based models were used where available and appropriate (e.g. energy and emissions). For other variables such as social cohesion and health we derived trends directly from stakeholder input. Horizontal consistency was nevertheless ensured by basing parameter settings and trends on the semi-quantitative trends, which included both stakeholder and expert input to maintain consistency with the narratives (Harmáčková et al., 2022). We conducted at least two internal review iterations of the quantitative projections for each indicator, making adjustments where necessary. This ensured that directions and magnitudes of change are aligned with the UK-SSP narratives, which describe internally coherent future worlds.

4.3. Legitimacy

Scenario modelling is often assessed with respect to credibility, saliency, and legitimacy (Rounsevell & Metzger, 2010). All three quality criteria are enhanced when researcher-driven and stakeholder-driven methods are combined (Star et al., 2016). Legitimacy of scenarios made within a single model is traditionally based on rigour and reproducibility, less on future-proof-ness of assumptions. Some assumptions are made explicit by appearing as exogenous variables, others are kept implicit as endogenous and structural. This gives modellers the power to deliberate what reality the model is going to replicate – a normative choice that determines model results as much as the parameters and calibration data.

The UK-SSPs reflect different socioeconomic systems and implicit ideologies, some of which are easy to imagine because they resemble the past and present, while others might be more difficult to imagine because they diverge from what is currently considered the norm. One example for a relationship that does not follow historical patterns is education and population growth, both in the global SSP5 (KC & Lutz, 2017) and in UK-SSP5. Empirical evidence suggests that birth rates decrease when education is increased (Adelman, 1963), but in SSP5 and UK-SSP5 both indicators grow in parallel. In a similar way, we struggled to model fossil-fuelled development in a high-technology world (UK-SSP5), because historical innovation cycles suggest that any significant further innovations in fossil fuel technology are not to be expected (Farmer & Lafond, 2016).

Making a model behave as qualitative narratives suggest it should, is challenging. A compromise for researchers then is to employ a mixed-methods approach, in which variables are projected within different models, which are not rigidly coupled. Legitimacy of the quantified UK-SSP projections draws on embeddedness within stakeholder derived narratives, minimising the risk that implicit worldviews fixed within a single integrated model would determine the outcomes. While this also implies that outcomes are prone to the disadvantages arising from participatory approaches, e.g. restricted reproducibility, legitimacy of the UK-SSP scenarios is based on local expertise and representation – values argued to be of particular importance for climate risk scenarios (Riddell et al., 2018). A mixed method approach based on stakeholder derived narratives also enables greater saliency and credibility, because it relies on a wider extent of sectorally- and locally specific expertise.

5. Conclusion

The quantitative projections presented here are underpinned by the UK-SSP narratives described in Harmáčková et al. (2022). We have used various spatial and sectoral levels in order to provide appropriate specificity for different user groups. The data can be applied as inputs to specific quantitative applications such as those used to evaluate climate risks, land use change, and pollution impacts. Climate risks can be evaluated for example by combining the UK-SSP projections with the UKCP18 climate projections, which are based on the RCPs. A complementary 1 km gridded UK-RCP dataset has been developed from the UKCP18 climate projections (Robinson et al., 2023) to use in such applications.

The results of our study suggest convergent outcomes for many socioeconomic indicators such as education and health when comparing UK-SSP1 and UK-SSP5, although these scenarios are based on very different narratives. Focusing on the same indicators we can also see convergent socioeconomic outcomes when comparing UK-SSP3 and UK-SSP4. Both UK-SSP1 and UK-SSP4 show high levels of technological change to reduce emissions. The associated economic transformation comes with socioeconomic benefits in UK-SSP1, while it comes with high inequality and net socioeconomic disbenefits in UK-SSP4. Both UK-SSP3 and UK-SSP5 show uncontrolled use of finite natural resources. UK-SSP5 assumes wealth based on a large material footprint, while UK-SSP3 is a scenario of institutional breakdown, poverty, and conflict, where subsistence living becomes the norm.

Importantly, the observed equifinality in the UK-SSP scenarios (Rounsevell & Metzger, 2010) does not imply that some scenarios are more likely or plausible than others. The convergent results for some indicators in UK-SSP1 and UK-SSP5 suggest that socioeconomics is an important driver to reduce challenges to climate adaptation. Converging results of some indicators in UK-SSP3 and UK-SSP5 suggest that uncontrolled natural resource use drives challenges to climate mitigation.

Given the diverse kinds of indicators and the structurally different scenarios covered in this study, we employed a mixed-methods approach that implies restrictions on the formal coupling between indicators. We suggest continued research on how qualitative and semi-quantitative SSP elements can be translated into quantitative projections at a maximum level of internal consistency, while being based on the local knowledge and views of representative stakeholders.

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

All data is openly accessible through the UK Climate Resilience Programme website: https://www.ukclimateresilience.org/products-of-the-uk-ssps-project/

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.crm.2023.100506.

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