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Scenarios for reducing the environmental impacts of the UK clothing economy

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ABSTRACT

In the 21st century the carbon emissions, material consumption, and impact on planetary boundaries associated with clothing have increased dramatically, driven in large part by fast fashion. The UK represents a typical, affluent, import-reliant Global North country, with clothing consumption per capita at double the global average and the impacts largely offshored. Progress towards a sustainable, circular clothing economy in the UK has been sluggish, as it has been globally. Here, we develop scenarios exploring how, over the coming two decades, the UK clothing economy could achieve the ambitious reductions in environmental impacts necessary to bring humanity's impact back within planetary boundaries. The scenarios consider the impacts of production- and consumption-focused changes, and the modelling uses material flow analysis to develop an assessment of energy consumption, carbon emissions, water consumption, and land use. We find that cleaner production and recycling alone could provide significant benefits for land and water use, reducing footprints by 60–70% by 2040. But to meaningfully reduce energy use, transformational changes will be required throughout supply chains at consumer and post-consumer stages. The same is true if the UK clothing economy is to be on track for net-zero by 2050, which requires these changes to be well under way within the next decade in order to halve emissions. Given the scale of change required, it seems highly unlikely that current clothing business models are compatible with a sustainable future.

1. Introduction

In the 21st century the annual carbon emissions of the fashion industry (including clothing and footwear) have increased by 30% (to 1.3 Gt.CO_2e) and material use has doubled to reach ~70 Mt (Niinimäki et al., 2020; Peters et al., 2021). The industry's emissions growth is thus similar to the global rate (IPCC, 2022), but its material footprint growth considerably faster (UN, 2022). Clothing production also accounts for 79 trillion litres of water use annually (Niinimäki et al., 2020), ~20% of all industrial water pollution (Bailey et al., 2022; Kant, 2012), 35% of oceanic microplastic pollution (Ellen MacArthur Foundation, 2017), and it places pressure on other planetary boundaries (Sandin et al., 2015) through land use, biodiversity loss and fertilizer overapplication (Cornell et al., 2021).

This growth in impacts has been driven by the proliferation of fast fashion culture (Niinimäki et al., 2020) in which fashion cycles have steadily shortened and purchasing clothing has become a weekly habit (Domenech et al., 2023), and an expanding global middle class largely found in China and other countries of south and east Asia (Peters et al., 2021). Neither trend shows signs of slowing. Unabated, material consumption of clothing and textiles could double again in the next decade (Bartl and Ipsmiller, 2023) and triple by 2050 (Ellen MacArthur Foundation, 2017). The carbon emissions from producing clothing and textiles could thus increase 35% by 2030 to over 400 Mt (Textiles_Exchange, 2022).

For clothing (and indeed consumer goods more broadly), the UK represents a typical case of an affluent, import-reliant Global North country. Clothing consumption is high at nearly 20 kg per person in 2019 (WRAP, 2022a) – around double the global average of ~9 kg (Niinimäki et al., 2020). The vast majority of the environmental impacts associated with this consumption – water use, chemical pollution, etc. – are shouldered by the low- and middle-income countries at the beginning of global textile supply chains such as China, Bangladesh and India. Indeed, less than 2% of the carbon footprint of UK clothing consumption occurs within UK borders (DEFRA, 2020). The UK's highly progressive climate targets, which legally bind the government to achieving net zero

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by 2050 with an interim target of a 78% reduction in CO_2 by 2035 (on 1990 levels), are thus blind (Millward-Hopkins et al., 2017) to 98% of emissions related to UK clothing consumption.

To become environmentally sustainable, the global textile industry needs to be transformed away from its current extractive, linear, and growth-focused configuration (Buchel et al., 2022) towards one compatible with a circular economy (Ellen MacArthur Foundation, 2017; Shirvanimoghaddam et al., 2020; Velenturf and Purnell, 2021). This must involve a combination of technical and social strategies to increase clothing lifetimes, repair, reuse and recycling (to reduce consumption and production to a minimum) and substitution with more sustainable fibres (to limit the impact of this minimal production). There is no easy fix (EAC, 2019). Production-side changes might include improved energy and resource efficiency in the multiple processes between extraction and the finished garment (Çay, 2018); sourcing of more sustainable fibres (Textiles_Exchange, 2022), such as those from bioprocessing organic wastes (Ribul et al., 2021); and reductions in pre-consumer waste from, e.g., pattern cutting (Reverse Resources, 2017). More systemic interventions might include increasing reuse and recycling of second-hand clothing (Farrant et al., 2010; Virgens et al., 2022) by increasing perceived value and durability; challenging consumer culture and the imperative for economic growth (Bauwens, 2021), by buying less clothing and keeping it in use for longer (Jung and Jin, 2014; Piippo et al., 2022), and by developing new business models (Papamichael et al., 2022). Overall, the sector must prioritises human and ecological health (Sharpe et al., 2022).

Some countries, such as Sweden and The Netherlands, have seen broad, albeit very limited and waste-centric progress towards circularity in the clothing sector (Brydges, 2021; Reike et al., 2022). More substantial progress is only observed at the subregional level in specific contexts, such as circular wool economies in Prato (Italy) (Saccani et al., 2023). But overall, many barriers remain. For example, regarding consumption, there is a gap between people's motivation and actions when it comes to sustainable purchasing – people's pro-environmental values have little relationship to the emissions related to their clothing (Nielsen et al., 2022), and the rate at which used clothing purchases replace new consumption can be under 50% (Castellani et al., 2015; WRAP, 2012a). Regarding substitution, purportedly more sustainable fibres do not always turn out definitively to be so (Ivanović et al., 2021), not least because the data on the environmental impacts of different fibres, fabrics and clothing is highly variable (Munasinghe et al., 2021). Moreover, the pace of change remains highly inadequate, and the dominant culture of fast fashion is very unlikely to be compatible with circular economy (Bartl and Ipsmiller, 2023). Official UK government sources indicate the carbon footprint of UK clothing has decreased substantially in the past decade, but other sources show negligible changes (Millward-Hopkins et al., 2023). In addition, consumption of new clothing continues to rise – from 1.03 Mt in 2010 (WRAP, 2019) to 1.3 Mt in 2019 (WRAP, 2022a) – and disposals to landfill and incineration in 2018 (400 kt) (Millward-Hopkins et al., 2023) were at a similar level as in 2010 (430 kt) (WRAP, 2012b).

This sluggish level of change contrasts with the targets proposed by leading institutions. *Textiles Exchange* propose a 45% reduction in global carbon emissions by 2030 on 2019 levels (for clothing, home textiles & footwear) (Textiles_Exchange, 2022). In the UK, WRAP's Textiles 2030 initiative aims to achieve a 50% reduction in the carbon footprint on 2019 levels (and a 30% reduction in water footprint) – in scope of this are the (voluntary) signatories, who currently account for over 62% of UK clothing market (WRAP, 2022b). The first progress report did not deliver good news – the carbon footprint of signatories increased 4.4% from 2019 to 2021 and the water footprint 1% (WRAP, 2022b). This was because interventions have largely involved moving to improved fibres – e.g., *Better Cotton Initiative* cotton or polyester from open-loop recycling – which has a modest impact on UK clothing's carbon footprint as a whole, thus leaving the benefits outweighed by growth in clothing consumption. A combination of substitution, recycling, and reductions in production and consumption – with ambitious changes on all fronts – will likely be required for the environmental impacts of the clothing sector to be meaningfully cut.

In the current work, we develop scenarios that explore how the UK clothing economy could achieve such ambitious reductions in environmental impacts – reductions that are in-line with those described above and, moreover, are necessitated by the challenge of bringing humanity's impact back within planetary boundaries (Steffen et al., 2015). We build upon a recently developed material flow analysis (Millward-Hopkins et al., 2023), adding a more thorough accounting of carbon emissions alongside energy, water and land use. Broadly described, the scenarios consider the impacts of two production-focused changes – large decreases in the intensity of clothing production, and a large upscaling in recycling – two consumption-focused changes – large increases in clothing reuse, and a decrease in overall clothing consumption. In short, we find that necessary reductions in the environmental impacts of the textiles sector require significant action on all these fronts.

2. Background and methods

2.1. The clothing system

Global clothing supply chains are difficult to analyse as they are dominated by small and medium enterprises that knit together a complexity of production processes (Luo et al., 2021; Moazzem et al., 2022). The starting point is the extraction and production of fibres, which could be natural such as cotton or wool (obtained via agricultural activities), semi-synthetic such as viscose (obtained via chemical processing of woody pulp) or man-made such as polyester or nylon (obtained via extrusion of petroleum-derived polymers). These fibres are spun into yarns, woven or knitted into fabrics, and then used to manufacture apparel. Clothes are distributed to retailers to sell to consumers, who eventually discard them (Sandin and Peters, 2018), at which point they may be resold, recycled into new fibres, downcycled into lower-quality materials such as rags or matting, or incinerated or landfilled such that – putting aside energy recovery – their value is lost completely (Amicarelli et al., 2022; Shirvanimoghaddam et al., 2020). This supply chain is summarised in Fig. 1, which also indicates for the UK clothing economy whether these activities occur mostly globally or domestically – a point discussed further in the results.

2.2. Material flow analysis

The foundation of the model of the current work is a recent material flow analysis (MFA) developed for the 2018 UK clothing system, prior to COVID19 (Millward-Hopkins et al., 2023). This mapped all flows of clothing related to the UK clothing economy, with the system boundaries chosen to include imported clothing and pre-consumer waste; UK production and retail of imported clothing; and various post-consumer pathways, from second-hand markets (in the UK and abroad), to recycling, downcycling, incineration and disposal. The data sources used included academic papers, government data, and non-peer reviewed literature and are fully described in the previous work, where the 2018 MFA output data upon which this work is built is also available.

MFA is underpinned by conservation of mass (Cencic and Rechberger, 2008). Systems are comprised of flows of materials between processes, any of which may contain stocks where material accumulates (rather than flowing elsewhere). The inflows entering a process are balanced with the outflows and change in stock, leading to the key equation:

$$\sum_{1}^{n} inflow_i - \sum_{1}^{m} outflow_j = stock\ change,$$

where, i indexes all n inflows into a given process, j indexes all m outflows, and the stock change at given process only. Systems can be linear

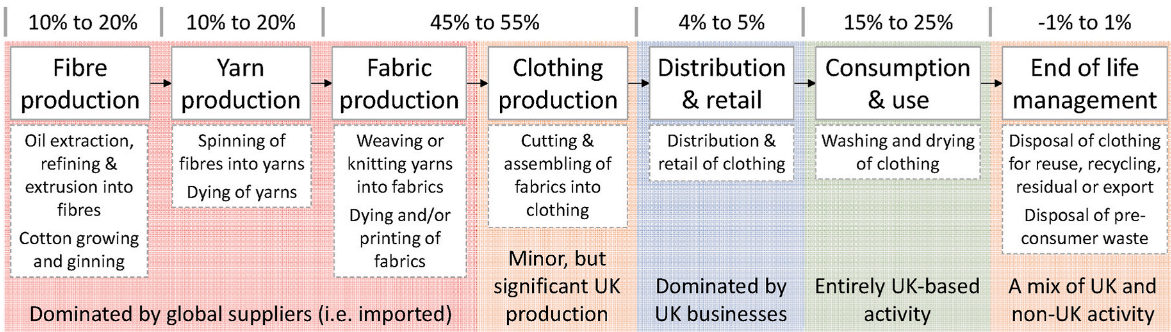

Fig. 1. Illustration of the main stages of the clothing supply chain, based upon various studies (Moazzem et al., 2022; Niinimäki et al., 2020; Sandin and Peters, 2018). Percentages along the top indicate the approximate amount that each stage contributes on average (not for a specific fibre, clothing type, or region) to the total carbon footprint of the clothing system – this is based upon data in reported in Niinimäki et al. (2020) and Peters et al. (2021). The shaded boxes correspond to the bottom line of text, which describes roughly where these impacts occur in relation to clothing consumed in the UK.

or circular – in the latter, flows may recirculate material between processes. The analysis may also be static or dynamic – in the former, a single point in time is considered or a system is assumed to be in steady state; in the latter, the temporal evolution of a system is considered. The characteristics of flows can also be specified, such as composition (breakdown of fibres, clothing types, etc.) or associated environmental, economic, social, or technical values (Iacovidou et al., 2017), which may behave in fundamentally different ways (Millward-Hopkins et al., 2018a). The MFA described in Millward-Hopkins et al. (2023) was simple, being linear and static and lacking flows' compositions. Consequently, it was easily solved in a spreadsheet model via repeated application of the above equation at each process in the system.

For the current work, we modify the 2018 MFA to obtain our baseline 2021 MFA by making two simple assumptions and a minor structural change. First, all 2018 flow values are increased by 5% to account for the increase in clothing and textiles placed on the UK market before to after COVID19 (WRAP, 2022b). Specifically, fibre consumption rose ~6% from 2019 to 2021. We round this down to 5% and assume this increase applies equally to all parts of the system – for example, imported and UK-made clothing are increased by the same 5%. The crudeness of this modification does not affect our core findings, but future work may benefit from a more refined baseline. Second, using updated government data (DEFRA, 2021), landfilled waste is reduced (from 19% to 13% of disposed waste) and other pathways are increased (from 81% to 87%; note that over 95% of this is energy-from-waste and incineration, and material recycling only becomes significant in our scenarios). Finally, the structural modification involves expanding the system upstream to separate fibre production from fabric and apparel production (see section 2.3 for an explanation). The system boundaries are not extended further upstream to raw material extraction, e.g., to include oil for polyester or wood for viscose. Instead, upstream impacts are included in the lifecycle assessment data described in section 2.3. The MFA structure is described flow-by-flow in the results, where discussion is more intuitive, and the calculation procedure is detailed fully in the Supplementary Information (Section 4).

We then expand the previous model to include recirculation of materials and the system's potential evolution until 2040 (see section 2.4), as well as an assessment of four environmental impacts (see section 2.3). Compositional data on the types of clothing (shirts, trousers, etc.) is not considered. And the fibre composition of flows is only considered in a simple, aggregate way – focusing on four fibres, with their composition fixed from 2021 to 2040 (at the values shown in Table 1). For example, the percentage of polyester (26%) is fixed from production through to all end-of-life pathways from 2021 to 2040. The justification for this approach is given in section 2.4.

Table 1
Summary of the environmental intensities input into the model for 2021. The mass-based composition is specified in brackets as (as %), based upon WRAP (2022a) data. All data is per tonne (T) of clothing material. Data is not taken directly from any particular sources, but instead set to illustrative values based upon a range of sources. These are largely from the systematic review by Munasinghe et al. (2021) ,[11] but also Niinimäki et al. (2020) ,[22] La Rosa and Grammatikos (2019) ,[33] Liu et al. (2020)[4], Steinberger et al. (2009)[5], van der Velden et al. (2014)[6], and Sandin et al. (2013)[7]. Where a value is simply assumed to be the same as that for a different fibre above, this is indicated with an asterisk (*); where a value is assumed based only upon intuition, it is indicated with a tilde (~). See the Supplementary Information for full details on these estimates.

	Energy (GJ)	CO_2e (T)	Land use (m^2)	Water use (m^3)
Fibre production				
Cotton (48%)	50[1,3,4]	2.0[1,2]	5,000[7]	5,000[1–4]
Polyester (26%)	90[1]	3.0[1,2]	~50	50[1,2]
Viscose (10%)	90[1]	3.0[1,2]	7,500[7]	200[1,2]
Other (16%)	130[1]	5.5[1]	~50	100[1,2]
Clothing production				
Cotton (48%)	100[1]	12[1,5,6]	~0	200[1]
Polyester (26%)	80[1]	10[1,5,6]	~0	200[1]
Viscose (10%)	100*	12*	~0	200*
Other (16%)	80*	10*	~0	200*
Recycling				
Cotton (48%)	−5[4]	−1.2[4]	−5,000[4]	−4,000[4]
Polyester (26%)	−9[4]	−1.8[4]	−50[4]	−40[4]
Viscose (10%)	−9[4]	−1.8[4]	−7,500[4]	−160[4]
Other (16%)	−13[4]	−3.3[4]	−50[4]	−80[4]

2.3. *Environmental impacts*

We estimate the environmental impacts of the UK clothing system by using life cycle assessment (LCA) data to calculate the supply chain impacts of clothing purchases, while reuse and recycling are accounted for via our MFA. We do not undertake an LCA ourselves but look to published studies in order to specify impacts of clothing of different fibres (and the reduction in impacts when discarded clothing is converted into new fibres for closed-loop recycling). LCA studies typically use a functional unit of a tonne or kilogramme of clothing/fibre, or of one item of clothing (with its weight also specified). Thus, the literature data we review can be converted into per-tonne *intensities* – $t.CO_2e$ per t of polyester clothing, etc. These intensities are then easily used to estimate systemic impacts of the UK clothing economy by multiplication with data from the MFA (e.g., tonnes of new clothing consumption, or tonnes of closed-loop recycling). Intensities are summarised in Table 1, and the LCA data underpinning them detailed in the Supplementary Information.

We draw upon LCA data on four environmental impact metrics: energy, greenhouse gas, and water footprints, and land use. These cover a wide range of the impacts of relevance to clothing consumption and to planetary boundaries (Cornell et al., 2021). 'Footprints' in this sense refers to the cumulative supply-chain impacts of clothing upstream from consumers – from extraction of fibres, through clothing production, to retail (i.e., all stages prior to *consumption & use* in Fig. 1). Greenhouse gas emissions are calculated over a 100-year time horizon, and land use measures the total land required to produce one tonne of fibre in one year. Water footprints nominally include blue, green and grey water and energy footprints nominally describe renewable and non-renewable primary energy – LCA literature is not always clear on the scope of assessment that has been undertaken in these cases (Munasinghe et al., 2021) and this introduces uncertainties into the present results. Ideally, an impact assessment of water pollution and nitrogen and phosphorus cycles would also have been made, however, no appropriate data was found in the existing LCA literature for estimating and projecting these impacts out to 2040.

The available LCA data is highly variable and uncertain. This is a well-known issue for the textiles sector, and researchers have argued the point candidly. Some suggest most of the existing LCA data is 'useless' due to it not specifying yarn thickness, which can influence impact data more than a shift from a low-to high-impact fibre (van der Velden et al., 2014). Others suggest that existing gaps in data make '*quantitative impact assessments partial at best, and even potentially misleading*' (Cornell et al., 2021). In the current analysis, some of these uncertainties may cancel out somewhat as data are averaged over many items of clothing. The issue of yarn thickness is one example: thicker yarns have a much lower energy and carbon footprints than thinner yarns when normalised by weight of material, but thicker yarns result in heavier fabrics per area of material (van der Velden et al., 2014). Other uncertainties may influence the scale of our results, but not the magnitude of the scenario interventions, ensuring our results remain meaningful for guiding action. Nonetheless, these various significant uncertainties must certainly be borne in mind.

Our accounting is also far from exhaustive. The direct impacts of end-of-life pathways such as incineration, transport involved in clothing reuse, and used clothing exports to the Global South are not considered. Generally, the impacts of incineration, and of personal transport involved in reusing clothing, are insignificant relative to the impacts of new clothing (Farrant et al., 2010; Levänen et al., 2021). However, there are exceptions – for example, rental business models where consumers make multiple trips via car can lead to higher emissions than the linear model of ownership and disposal (Levänen et al., 2021).

Note also that the use-phase is not considered, but this is a reasoned choice. Interventions for reducing use-phase impacts (e.g. less frequent, lower-temperature or more efficient laundry cycles, lower-impact household detergents) are more closely related to studies of residential energy and water use than to the circular economy interventions considered in our scenarios. They are thus left out of scope, but their significance should be noted – the UK carbon footprint of washing and drying is estimated at over 20% of the total carbon footprint of UK clothing (WRAP, 2022a).

A detailed, bespoke LCA of the UK clothing system, considering the composition of clothing purchased – both the apparel and fibre type – and the specific regions of origin, would be a valuable direction of future work and would rectify limitations of the current work. Research developing more reliable methods of tracing the impacts of specific clothing items is underway (Shou and Domenech, 2022). Such data could be fed into the scenarios we develop here. For the present work, however, we set intensities to the round values summarised in Table 1, which are representative of the range emerging from the literature. Details on precisely how these values were estimated is left for the Supplementary Information, aside from two important points:

First, we do not use different impact intensities for clothing produced in the UK, and that imported. This is less-than-generous to UK production, given (for one thing) the relatively low-carbon nature of UK electricity production. However, UK production is relatively small compared to imports, and even clothing that is technically made in the UK largely relies upon imports of fibres, yarns or fabrics, which together account for much of the impacts. A detailed analysis of what percentage of fibre, yarns, and fabrics used in UK clothing consumption are produced domestically, or imported, is a challenge for future work.

Secondly, we model the benefits of closed-loop recycling by attaching negative impacts to the flow of recycled material, which reflect avoided virgin material use. An alternative approach would be to assign positive environmental impacts to fibres recycled from UK consumption, then recirculate them into fibre production in the MFA so they directly offset the mass flow of virgin fibres (just as the MFA accounts for reuse directly, by modelling reductions in UK clothing consumption). Mathematically, however, both approaches lead to identical outputs. The negative values we use are based upon data from Liu et al. (2020). This suggests that relative to virgin cotton, recycled cotton has 10% lower energy footprint, 60% lower carbon footprint, 80% lower water footprint, and negligible land use. So for water use the 'impact' of recycled cotton (-4000 m^3/T) is -80% that of primary production (5000 m^3/T). These savings are assumed to apply to all fibres, which represents a further limitation of our approach – in practice savings for different fibres will vary with recycling technology (in particular, whether mechanical or chemical recycling methods are used see e.g. (Schmidt et al., 2016) and supply chain structure. Note, however, this limitation is mitigated by the fact that cotton is half of the UK fibre mix.

2.4. Scenario development

We develop five scenarios to consider pathways of the UK clothing

Table 2
A summary of the narratives and changes underpinning the five scenarios developed, including business-as-usual (BAU), two production-focussed scenarios (P1 & P2), two consumption-focussed ones (C1 & C2), and a sixth which combines these into a single model run (PC).

Scenario	Narrative	MFA dynamics	Environmental impact
BAU	Baseline	Fixed, except landfill waste decreases to zero by 2035	Impact intensities of production decrease at BAU rates
P1	Cleaner production	*As for BAU*	Impact intensities of production decrease above BAU rates
P2	Cleaner production & High recycling	*As for BAU, plus:* **Recycling increases** significantly, by diverting material from residual waste, downcycling, and used exports **Pre-consumer waste decreases**	*As for P1*
C1	High reuse	**UK reuse increases** significantly, by diverting material from residual waste and from used exports	*As for BAU*
C2	High reuse & Less consumption	*As for C1, plus:* **'Effective consumption' decreases** by 50%	*As for BAU*
PC	All interventions	*As for P2 and C2*	*As for P1*

[1] For example, see the BBC Future article: https://www.bbc.com/future/article/20200310-sustainable-fashion-how-to-buy-clothes-good-for-the-climate.

[2] To be clear, ROW production is not all global production, but rather just that providing UK imports.

[3] Note that another pseudo-process is used here, namely *Collections*, as we only know the destination split of material from these three collection routes in aggregate, not individually.

system out to 2040. Modelling these involves calculating changes in both the MFA and the environmental impact intensities of Table 1, to ensure these are consistent with the five scenario narratives that now described (which are summarised in Table 2).

2.4.1. Scenario 1 – BAU

The first is simply a baseline, business-as-usual scenario ('BAU' herein). For this, the MFA is assumed to remain the same from 2021 to 2040 – aside from landfill, which is assumed to decrease and reach zero by 2035, consistent with UK government policy (other disposal routes replace it, primarily incineration). This fixed projection is in some ways more ambitious than current trends – e.g., new clothing consumption has risen slightly over the past decade – but it nonetheless offers a reasonable baseline. For environmental impacts, their intensities are assumed to decrease annually by fixed percentages, and we attempt to make these consistent with previous trends, or in some cases business-as-usual forecasts (such as the land-use intensity of cotton). These percentages are summarised in Table 3, and their derivation described in the Supplementary Information.

2.4.2. Scenario 2 – P1

The second and third scenarios are production-focussed. The second ('P1') assumes the same MFA as BAU and the same composition of the main four fibre types, but more rapid decreases in the environmental intensity of production. These are calibrated to reflect improving efficiency of agricultural and industrial processes, and granular changes in fibre mix from virgin materials to 'improved' ones such as organic cotton or PET-bottle-derived polyester (see the Supplementary Information for a detailed explanation). Fibres from closed-loop recycling are instead modelled explicitly via the negative intensities in Table 1.

2.4.3. Scenario 3 – P2

The third scenario ('P2') assumes the decreased intensities of P1 alongside changes to the system that:

i. decrease pre-consumer waste, i.e., the material arising as offcuts and other waste when clothing is produced;
ii. substantially increase recycling, by capturing material currently sent to residual waste, and material currently exported with the intention of being reused, but that is instead disposed in places such as West Africa (Greenpeace, 2022; Manieson and Ferrero-Regis, 2022).

2.4.4. Scenario 4 – C1

The fourth and fifth are consumer-focussed scenarios. The fourth ('C1') assumes significantly increased levels of reuse of clothing within the UK. This is achieved by:

i. redirecting clothing currently sent to residual waste to the UK collection and sorting system – which supplies UK second-hand markets – and directly to UK reuse via platforms such as eBay;
ii. reducing exports of used clothing and diverting this clothing to UK reuse.

For total UK consumption, scenario C1 assumes a fixed level of 'effective consumption', defined as:

$$\text{consumption}_{\text{effective}} = \text{consumption}_{\text{new}} + \text{RR} \times \text{consumption}_{\text{used}}$$

where RR is the replacement rate: the rate at which items of new clothing are offset by purchasing a used item. Suggested replacement rates reported in the literature range from 30% (WRAP, 2012b) to over 80% (Farrant et al., 2010), but the methodologies raise questions, as discussed in the Supplementary Information. In any case, scenario C1 assumes reduced consumption of new clothing due to increased consumption of used clothing, but because replacement rates are under 100%, the former falls slower than the latter rises.

2.4.5. Scenario 5 (C2) and combined scenario PC

Scenario C2 is the same as C1, but it also assumes a linear reduction in effective consumption, which reaches 50% by 2040. This could also be interpreted as doubling the current lifetimes of clothing items, doubling the frequency of use of the clothing people own, or some balance of the two. The former does not imply individuals keep clothing items twice as long, only that clothing items last twice as long – irrespective of the number of owners they pass between via second-hand markets. Note also that, as mentioned in the introduction, UK clothing consumption per capita is currently around double the global average, so a 50% reduction would reflect the UK meeting this global average. Given all this, it appears a reasonable aspiration.

Finally, we model a sixth scenario (PC), which is simply an aggregation of all the changes assumed in scenarios P1, P2, C1 and C2 combined into a single maximum-ambition model run.

2.4.6. Scenario modelling details

Full details describing how the scenarios are parameterised and modelled are included in the Supplementary Information. Here, three key points are highlighted:

First, we emphasise that, although the model is dynamic, the calculations remain simple. A bespoke Python script is utilised to mass balance the system (using a yearly timestep) and fill gaps between the available input information on flows and processes. The scenarios are driven largely by exogenous variables – for example, in scenario P2, recycling as a fraction of new consumption is set to increase linearly each year, at a rate that brings residual waste to zero by 2040. Further, to avoid the use of calculus or numerical methods (to ensure the model remains useable by a wider group of people) a linear MFA system is modelled, but that still captures circularity. This is done by assuming a one-year time-lag between reuse and new consumption. So if, in year *t*, effective consumption is specified exogenously (as $C_{\text{effective},t}$), then the used clothing that became available in year *t-1* ($C_{\text{used},t\text{-}1}$) is used to calculate new consumption in year *t* ($C_{\text{new},t}$) via the equation introduced above:

$$C_{\text{new},t} = C_{\text{effective},t} - \text{RR}_t \times C_{\text{used},t\text{-}1}$$

Similarly, as closed-loop recycling is modelled by assigning negative environmental impact values to recycled material, the MFA itself can also remain linear in this respect.

Secondly, we emphasise that the scenarios are driven by our assumed narratives, rather than being driven by specific policy proposals or some other predicted future intervention. In short, the results reflect our

Table 3
A summary of the yearly changes in environmental impacts intensities that are assumed for the business-as-usual scenario. How these are derived is discussed in the Supplementary Information.

	Fibre production				Clothing production			
	Cotton	Polyester	Viscose	Other	Cotton	Polyester	Viscose	Other
Energy	−0.33%				−0.33%			
GHGs	−1.5%				−1.5%			
Land use	−1%	0%	−1%	0%	0%			
Water use	−1%	0%	−1%	0%	0%			

assumptions – the questions explored are along the lines 'if the system changed in way X, how would total environmental impacts change?' Further, the changes assumed to underpin each scenario are implemented rather strongly, making each ambitious in its own way. Results thus reflect theoretical assessments of strong ambition occurring in different areas of the clothing system, but no scenario should be considered a 'forecast' – and none can be considered most likely. In reality, the most plausible future is one with a moderate level of ambition occurring in all the areas each scenario explores separately. Because the calculations underpinning the scenarios are mostly linear, results for such a future would lie halfway between results for BAU and PC.

Finally, there are two reasons why we do not consider changes in the composition of the resource flow regarding the main four fibre types. First, there are the uncertainties discussed above, which produce considerable overlap in the carbon footprints of clothing of different fibres (Millward-Hopkins et al., 2023). This makes it impossible to determine with any confidence whether shifting from one broad fibre group to another (e.g. from polyester to cotton) will provide substantial carbon benefits, unless detailed and reliable supply chain and LCA information on the specific products under analysis is available (it typically is not). In contrast to this reality, public and media discourse often incorrectly states with misplaced confidence that switching from, say, polyester to cotton will bring considerable climate benefits.[1] By focusing upon actions with definite benefits, we hope to contribute to moving public discourse away from these misleading simplifications. Second, there has been little change in the high-level fibre composition in UK clothing over the past decade (WRAP, 2020). The only substantial change since 2019 has been a small shift away from viscose (WRAP, 2022a), which represents a small fraction (<10%) of the total resource flow and for which carbon footprint estimates in the literature are perhaps most variable and sometimes reported as negative (Munasinghe et al., 2021).

3. Results

3.1. Material flows in 2021

Production to consumption: The material flow analysis starts from the production of fibres – which occurs mostly outside the UK – then moves through production of yarns, fabrics and clothing, which are merged under *UK production* and *ROW production*[2] (rest-of-world; Fig. 2). Flows from UK and ROW production are then merged in the pseudo-process of *Arisings*, the flow from which is split between *Consumption* of new clothing and *Exports*. This is done as data for UK production and exports suggest exports are larger, implying that some clothing is imported and then re-exported. However, it is not clear how imports and UK production are each split between UK Consumption and Exports. Finally, note there are also flows of pre-consumer waste, from UK and ROW production to UK *Residual waste* and *non-UK disposals*, respectively. In the base year (Fig. 2), UK consumption is estimated at 1116 kt. And at 186 kt (including pre-consumer waste) UK production is 12% of the size of ROW production. Flows of pre-consumer waste are significant, particularly that relating to ROW production. To reiterate, all these data are from previous work (Millward-Hopkins et al., 2023), but with a simple scaling factor applied to update from 2018 to 2021.

Consumption to reuse and recycling: After consumption, new clothing may pass directly to *UK reuse* – via market places such as eBay and Facebook, or direct 'hand me down' within families or communities – or be collected[3] with the intention of it being reused or recycled – via *Charity shops*, *Textile banks*, or *Other collection* methods such as kerbside collections by local councils. After collection via these routes (shown in green on Fig. 2), clothing may either be reused in the UK (green), exported as *Used Exports* (blue), *Downcycled* (blue), or disposed to *Residual waste* (red). In 2021, over 60% of new consumption (699 kt) follows these pathways. However, only 30% of the material collected by charity shops, textile banks, or other collection routes is currently reused in the UK, while 60% is exported (374 kt), a few percent heads to downcycling and residual waste, and a negligible amount is recycled into clothing fibres. Of the clothing exported, potentially only 60% is reused. The total amount of clothing reused in the UK (275 kt) ends up not dissimilar to the amount exported then reused elsewhere (224 kt).

Other post-consumption pathways: Most clothing not collected or reused passes to residual waste, either through *Kerbside* waste collections or household waste recycling centres (*HWRC*). Previous work suggested a small amount of clothing consumption remains *Unaccounted* for after mass balancing, potentially reflecting annual growth in the collective size of the UK wardrobe. Residual waste in the UK is mostly sent to incineration (which mostly uses energy recovery), and the MFA suggests 346 kt of clothing follows this pathway. The clothing sent to landfill is about 56 kt, or 5% of new consumption. Finally, *Non-UK disposals* of clothing that are directly related to the UK clothing economy are considerable (457 kt), and indeed are larger than the residual clothing waste arising in the UK itself (421 kt). The primary contributor is pre-consumer waste arising from the global supply chains supporting UK consumption, which could be understood as waste 'embodied' in UK imports. Used clothing exported by the UK that does not end up being

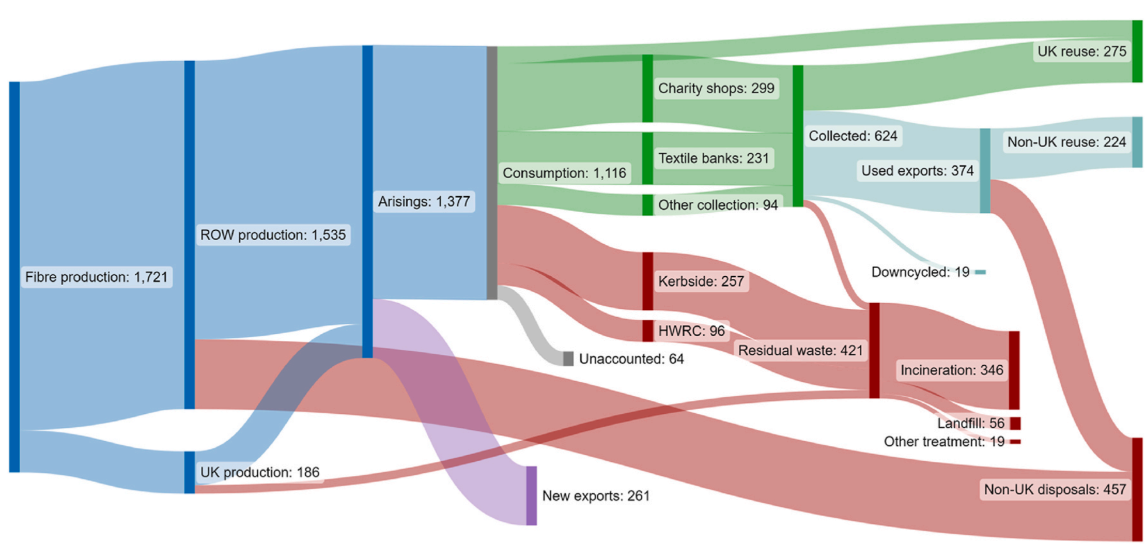

Fig. 2. Material Flow Analysis in the base year of 2021, modified from Millward-Hopkins et al. (2023). All values are in kilotonnes (kt) of clothing, and include all fibres. Figure made in SankeyMATIC.

reused is also significant.

3.2. Material flows in the scenarios

In BAU, and the "cleaner production" of scenario P1, the 2021 MFA is unchanged through years 2021–2040 – aside from the elimination of landfill waste, with the material instead passing to incineration. Similarly, scenario P2 – "cleaner production and high recycling" – has fixed values for arisings, consumption and exports through 2021–2040, however, the pre-consumer waste fraction is assumed to fall linearly from the initial value of 20%–10% by 2040. In other words, the amount of clothes produced and consumed is assumed to be fixed, but material efficiency improvements lower material input. This leaves fibre production in 2040 11% lower than in 2021 (Fig. 3, top).

Post-consumption, however, is where substantial changes in scenario P2 occur. An increasing amount of clothing is assumed to be sent directly to recycling after use – which implies separate collections of households' clothing waste – with this increasing at a rate that all but eliminates consumption to residual waste by 2040. Visually, this is shown by the near absence of red flows from consumption in Fig. 3 (top). This doesn't mean there is no UK residual waste, but rather that what does arise is from pre-consumer waste, and recycling plants where conversion rates are ~70–90% (we assume 85%; Esteve-Turrillas and de la Guardia, 2017; Liu et al., 2020; Yousef et al., 2019; Zamani et al., 2015). Scenario P2 also assumes that used exports decrease fast enough to almost eliminate associated non-UK disposals by 2040, with material diverted to UK recycling. There is thus an implicit assumption that this diverted material is of low quality, while the higher quality exports that are currently reused outside the UK remain exported. Again, this is visualised by the negligible red flow – here from used exports to non-UK disposals (Fig. 3; top).

Scenarios C1 ("high reuse") and C2 ("high reuse and less consumption") also show large differences from BAU. In C2, the increased rate of reuse, and assumed halving of effective consumption by 2040, reduce new consumption to 410 kt (Fig. 3, middle). Around 90% of new clothing consumption is assumed to be directly reused, or collected for reuse and recycling. The majority of collected clothing is then assumed to be reused in the UK, as used exports decrease substantially – to only 10% of collections, down from the 60% share in 2021. Visually, Fig. 2 (middle) indicates this by showing the outflows from consumption and collected material to be dominated by green flows. Accordingly, non-UK disposals decrease ~80% relative to BAU (to 102 kt). When all the changes of the other scenarios are combined into the "all interventions" PC scenario, new consumption is ~3% higher than in C2, as some of the clothing assumed to be reused in C2 is instead recycled. However, fibre production and non-UK disposals remain lower than in C2, due to the

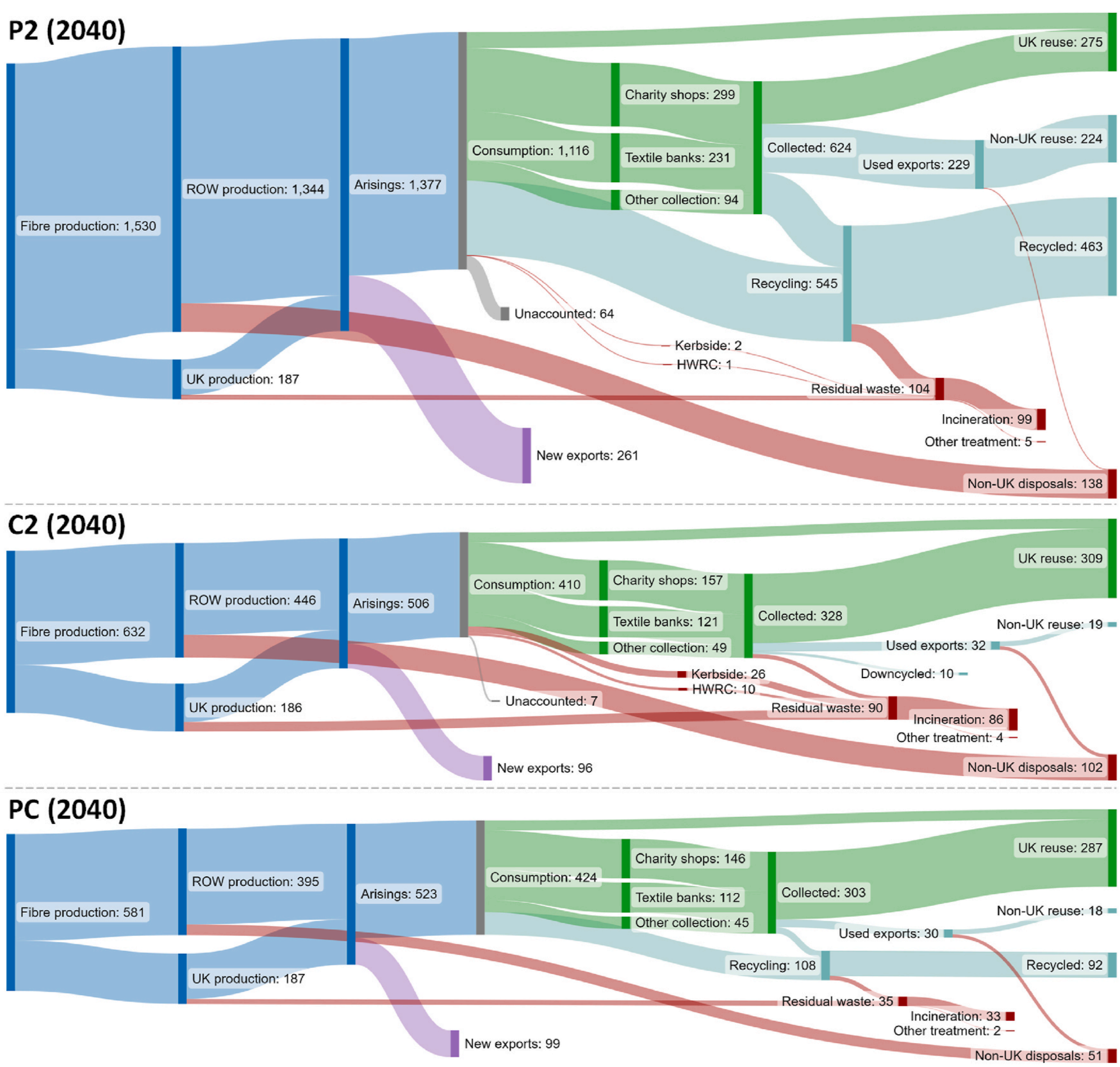

Fig. 3. Material Flow Analysis in 2040 for the P2, C2 and PC scenarios. All values are in kilotonnes (kt) of clothing and include all fibres. Each panel has a similar scale (i.e. the size of one kt), but they are not identical.

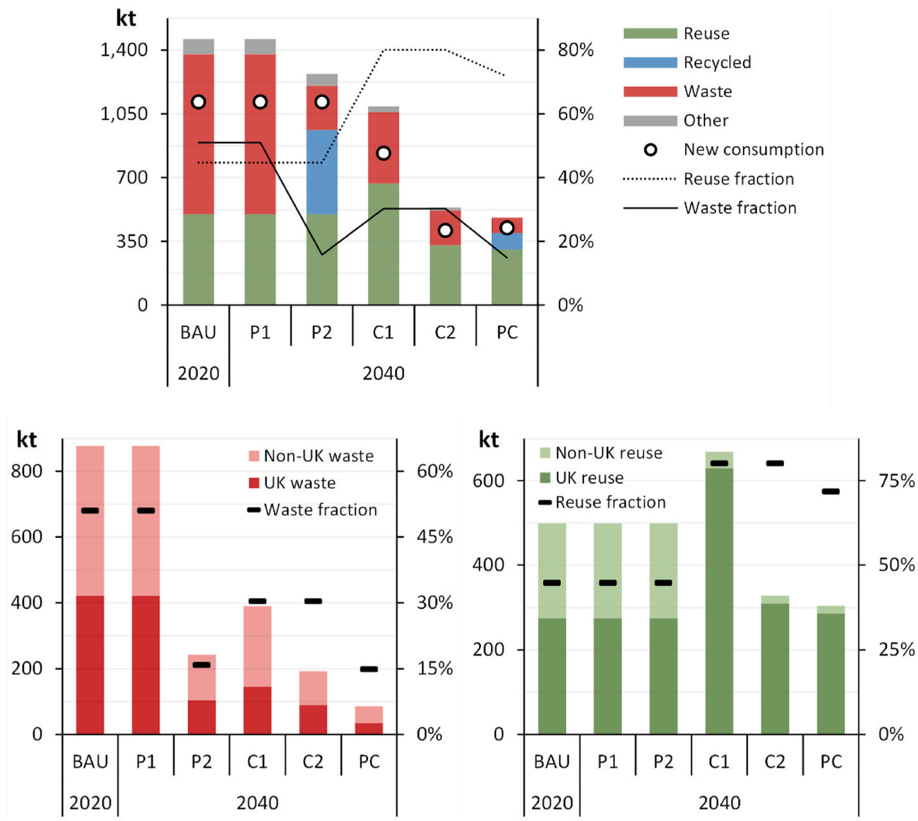

Fig. 4. Key material flow statistics from the scenarios (top panel), including new consumption, total reuse, recycling, waste, and other flows (which include downcycling and unaccounted flows, as visible in Figs. 2 and 3 Sankey diagrams). The reuse and waste fractions are also shown, which the former normalised by total new consumption and the latter by total fibre production. All mass data is in kilotonnes. The bottom panels show the waste (left) and reuse (right) data, but spilt by the share occurring within the UK and outside of it.

reduction in PC of pre-consumer waste.

Fig. 4 compares key statistics across the scenarios in 2040 to BAU:

1) The top panel shows that new consumption remains flat in scenarios BAU, P1 and P2, before falling 25% in scenario C1, and over 60% in scenarios C2 and PC.
2) The sum of UK residual waste and non-UK disposals ('waste' in Fig. 4) decreases substantially in all but scenario P1, due to this focusing upon cleaner production only. This results in the ratio of waste to total fibre consumption (the 'waste fraction') falling from 51% in BAU and P1, to ~15–30% in the other scenarios. Note, however, that even with the increased reuse of scenario C1 non-UK disposals remain reasonably high (Fig. 4, bottom-left).
3) Reuse only rises in scenario C1 – and UK reuse here more than doubles (Fig. 4, bottom-right). Due to reductions in effective consumption in scenarios C2 and PC, total reuse falls below BAU, but UK reuse increases slightly (Fig. 4, bottom-right) and reuse as a fraction of total new consumption increases from under 45% to over 70% (the 'reuse fraction').
4) By definition, recycling increases substantially in P2 – to nearly 500 kt, or 30% of total fibre production (up from ~0 in BAU). It is less significant in scenario PC, reaching 92 kt, or 16% of total fibre production.

3.3. Environmental impacts

So far, we have discussed results regarding flows of material and, given our assumptions, how these change across the scenarios. Of equal interest are the consequences of these changes for the environmental impacts of the UK clothing economy. Fig. 5 shows these changes for each scenario for the four environmental impacts considered. Existing, related, or proposed target reductions are indicated, where possible. Results are discussed for each impact in turn.

3.3.1. Energy

Under BAU, the energy footprint of UK clothing reduces marginally by 6% from 2021 to 2040. In P1 and P2 the reductions roughly triple, reaching 17–19%. The cleaner production of P1 brings limited reductions, as future improvements in energy efficiency are relatively small compared to carbon – an assumption based here on International Energy Agency forecasts (IEA, 2020). The addition of recycling in scenario P2 brings little extra benefit, as recycling itself is energy intensive. Higher reuse in scenario C1 reduces BAU energy use more significantly – by 32% by 2040. When combined with the lowered consumption of scenarios C2 and PC, energy reductions reach 65–70%.

We are unaware of existing, or applicable targets for the future energy footprint of UK clothing, and it is difficult to know where to begin in proposing one. However, as energy use tends to correlate with environmental impacts more broadly (Huijbregts et al., 2010), a target could prove valuable.

3.3.2. Carbon

The carbon footprint of UK clothing in BAU reduces more significantly than energy, falling 25% by 2040. This is due to the long-term decrease in carbon intensity observed in IO data from 2000 to 2019 (DEFRA, 2020), which we assume continues. Scenario C1 achieves a reduction of 44%, and the cleaner production in scenarios P1 and P2 drives a 58–60% reduction. P2 does not change significantly from P1, as the former's increase in recycling only reduces carbon emissions of fibre production, while 75–80% of the impact of clothing occurs downstream in spinning, weaving, etc. (steps which recycled fibres still undergo). In C2 and PC, reduced consumption allows for much larger reductions – of 72% and 85%, respectively, by 2040.

Defining targets for carbon emissions is more straightforward than for energy. First, WRAP's voluntary initiative, *Textiles 2030*, proposes to reduce the total carbon footprint of new clothing by 50% in 2030 relative to 2019 levels, and aim for net zero by 2050 at the latest (WRAP, 2021). It also seems reasonable to compare our scenarios with broader

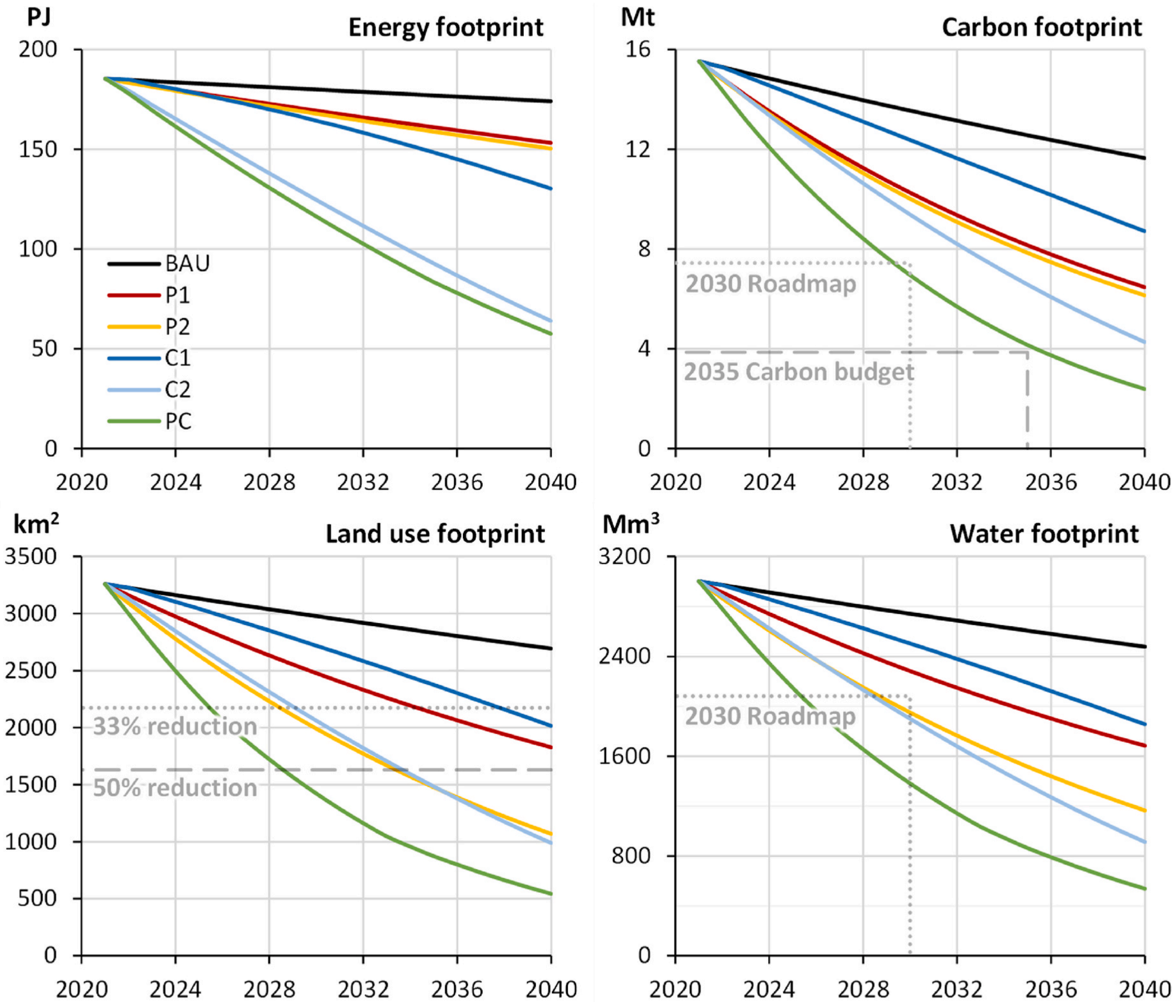

Fig. 5. Environmental impacts of the UK clothing economy from 2021 to 2040 in the six scenarios for energy (petajoules), carbon (megatonnes of CO_2e), land use (square kilometers) and water (million cubic metres). Existing, related, or proposed targets are shown in grey where applicable (see main text for details).

UK government targets, which include a 78% reduction in greenhouse gas emissions by 2035, on 1990 levels, increasing to 100% by 2050. Concerningly, Fig. 5 shows that only scenario PC meets the WRAP 2030 target, and none meet the UK Government 2035 target. Scenario C2 meets the WRAP target in 2035, and PC meets the UK government target only a year late. But the others remain far off course.

3.3.3. *Land*

Under BAU, the land footprint of UK clothing reduces by 17% from 2021 to 2040. Scenarios P1 and C1 increase this significantly to 38–44%. Scenarios P2 and C2 are much more effective still, achieving reductions of 67–70%. In scenario P2, fibre recycling becomes a highly effective means of reducing land footprints, as supply chain land use footprints are highly concentrated in virgin fibre production. Indeed, for land use, scenarios P2 and C2 lie closer to each other than for any of the other impacts. Finally, in scenario PC, the substantial land use reductions achieved through reduced consumption and increased reuse in C2, combine with the benefits of recycling and land-use efficiency in P2, to reduce land use by a considerable 83%.

As for energy, we are unaware of existing targets for the land use footprint of UK (or global) clothing consumption. However, we can speculate usefully. Consider that land use footprints in Europe – within which the UK is around average (Koslowski et al., 2020) – are twice the global average and nearly 50% higher than global biocapacity per person (Weinzettel et al., 2013). Moreover, the global planetary boundary for land system change – related to land use and biodiversity loss – has potentially been crossed already (Newbold et al., 2016). These observations suggest that the UK land footprint is currently 50–100% above where it should be. A 33–50% reduction would thus bring the UK in line with the global average and potentially within planetary boundaries – and it would be reasonable for the clothing sector to at least match this, as soon as possible. A comparison with our scenarios shows that all but BAU achieve a 33% reduction by 2040, P2 and C2 achieve a 50% reduction in the mid-2030s, and PC achieves this 50% reduction before 2030. Next to the carbon targets, this speculative comparison is relatively optimistic.

3.3.4. *Water*

The water footprint in BAU, P1, C1, and C2 fall by the same amounts as the land use footprint falls (17%, 38%, 44%, and 70%, respectively). This is the result of our assumed, annual reductions in impact intensities being the same for water and land use footprints (see Table 3). Scenario P2 achieves a slightly lower reduction in water footprint (61%) than it did for land use footprint (67%), as recycling requires significant water use to manufacture recycled fibres into clothing. Nonetheless, scenario PC is almost as effective for reducing water use as land use, achieving a 82% reduction (compared to the 83% for land use).

A water footprint target is also proposed by WRAP's voluntary initiative, *Textiles 2030*, namely, to reduce the total water footprint of new clothing by 30% in 2030 relative to 2019 levels (WRAP, 2021).

Fig. 5 shows a relatively optimistic picture, with scenarios P2, C2, and PC meeting this early, and P1 and C1 by the mid-to late-2030s.

4. Discussion and conclusions

These scenarios describe how the UK clothing economy could evolve in the next two decades to explore potential changes in environmental impacts. They are driven by modelling assumptions and hence, rather than being forecasts, they show how impacts would be affected if the clothing system were to change in particular ways. Some scenarios assumed substantial improvements in specific areas of production (e.g. decreased impact intensity per-tonne of clothing) and consumption (e.g. large increases in clothing reuse). Changes restricted to particular areas of the system, even with the high degree of ambition our scenarios assume, will not be sufficient to address the environmental challenges that the clothing system faces. Neither will these challenges be overcome by marginal changes across all the areas the scenarios explore separately (a future which would lie about halfway between BAU and the most ambitious scenario PC, and is perhaps more plausible than any of the scenarios themselves; see Fig. 5).

To meaningfully reduce energy use and climate change impacts, transformational changes are required both throughout the supply chain (to increase the efficiency of production and scale-up closed-loop recycling) and at the consumer and post-consumer stages (to maximise reuse of clothing and reduce the rate of new purchasing). These changes must be well under way within the next decade for the impacts of UK clothing consumption to be on track to meet net-zero by 2050. For land and water use impacts the picture is more positive, because closed loop recycling is more effective for reducing these impacts than it is for energy and carbon impacts. On the other hand, land use of the clothing system should arguably be reduced more dramatically than we considered above, given the pressures already posed on land use by food (Gerten et al., 2020) and bio-derived fuel in net-zero futures (Smith et al., 2016), not to mention the plethora of less land-intensive ways of producing clothing that exist. For water use the issue is less the absolute footprint (in contrast to carbon emissions), but whether the water use embodied in UK clothing consumption occurs in already-water-stressed regions (Motoshita et al., 2020) – an analysis well beyond our scope here.

WRAP's preliminary work mapping a pathway meeting their *Textiles 2050* targets (to halve emissions from UK clothing and reduce water use by 30%) comes to a similar conclusion (WRAP, 2021), but is weighted more strongly towards production-side changes. WRAP calculate that, from 2019 to 2030, more low carbon energy, cleaner industrial processes, and improved and recycled fibres could reduce emissions by 36%, while increasing reuse and longevity of clothing only reduce emissions by 14%. In contrast, although we assume similar interventions, production- and consumption-side changes contribute roughly equally to emissions reductions in the most ambitious scenario.

The magnitude of the transformation we outline cannot be understated. The most ambitious scenario – the only one close to a net-zero consistent pathway – assumes annual improvements in the environmental efficiency of clothing production far above the historical rate; reductions in pre- and post-consumer waste that together reduce waste to 15% of fibre consumption (from over 50% today); that *all* clothing discarded by households is sent to reuse or recycling (compared to under 50% today); and finally, perhaps most notably, that clothing consumption reduces by 50% to meet the global average. It remains an open question whether transformations of this scale are compatible with the business models currently in operation in the clothing industry, and the singular focus on financial return from capital investment that in turn underpin these (Bauwens, 2021; Corvellec et al., 2021).

All this said, there are various limitations to our work that should be borne in mind when considering these conclusions. Perhaps most importantly, the substantial uncertainties associated with environmental impact data in the clothing sector must be reiterated. These have implications for our comparison between scenario outputs and the various targets discussed in section 3.3. Regarding these scenarios, it is possible we have underestimated the improvements that could be made in fibre and clothing production. Relatively high-impact fibres may be phased out in ways we have not considered; novel chemical and biological recycling processes could emerge that reduce the impacts of fibre production below what we modelled (Ribul et al., 2021); renewable energy technologies could be deployed for spinning and weaving more quickly than our input carbon intensities implicitly assumed. On the other hand, it will be difficult to rapidly displace the incumbent fibres used in the clothing system. Where this is being done (for example, using recycled polyester derived from single-use plastic bottles) it appears to be another case of one industry relying upon the unsustainable practices of another for its sustainability credentials. This is a tenuous situation seen in other sectors (Millward-Hopkins and Purnell, 2019; Millward-Hopkins et al., 2018b). Our omission of the use stage of clothing could also be challenged, as this accounts for nearly a quarter of the clothing system's impacts. However, this omission would only affect our conclusions if a disproportionately high amount of the environmental impacts of the UK clothing sector could be saved at the use stage. In any case, in the longer-term this becomes irrelevant – net-zero must be met by all clothing stages: supply chains, in use, and post-consumption. For this future, nothing less than a complete transformation of the sector will suffice.

CRediT authorship contribution statement

Joel Millward-Hopkins: Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft. **Phil Purnell:** Conceptualization, Methodology, Formal analysis, Writing – review & editing. **Sharon Baurley:** Conceptualization, Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Phillip Purnell reports financial support was provided by UK Research and Innovation.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2023.138352.

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